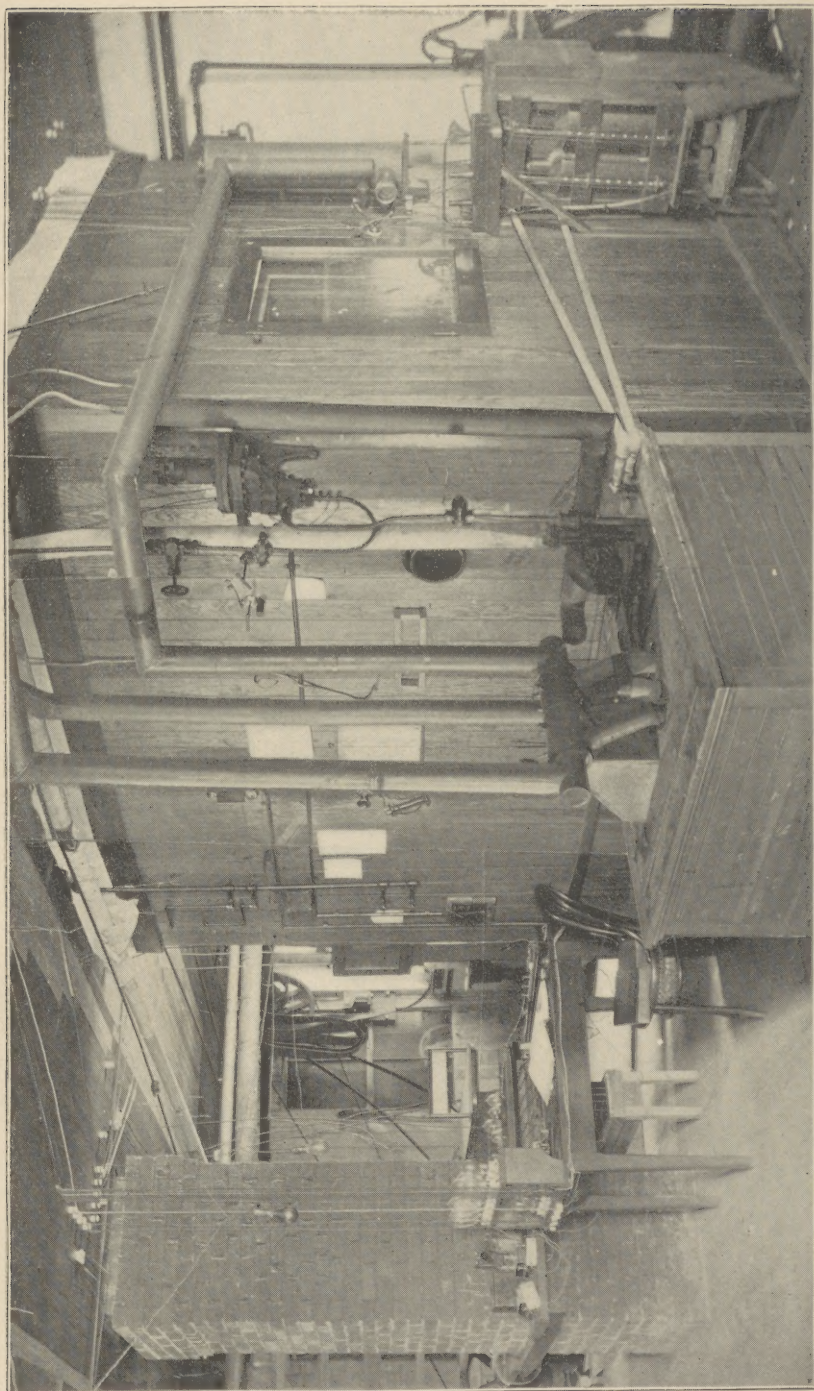




GENERAL VIEW OF THE ATWATER-ROSA RESPIRATION CALORIMETER.

Respiration chamber in center of background. Refrigerating tank in center of foreground. Water meter on the right. Observer's table on the left.

U. S. DEPARTMENT OF AGRICULTURE,
OFFICE OF EXPERIMENT STATIONS.

DESCRIPTION
OF
A NEW RESPIRATION CALORIMETER
AND
EXPERIMENTS ON THE CONSERVATION OF
ENERGY IN THE HUMAN BODY.

BY

W. O. ATWATER, Ph. D.,
Professor of Chemistry, Wesleyan University,

AND

E. B. ROSA, Ph. D.,
Professor of Physics, Wesleyan University.



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U. S. DEPARTMENT OF AGRICULTURE,
OFFICE OF EXPERIMENT STATIONS,
Washington, D. C., March 2, 1899.

SIR: I have the honor to transmit herewith a report describing a respiration calorimeter of special construction and experiments with this apparatus on the metabolism of matter and energy and the conservation of energy in the human body. The investigations described in this bulletin were made at Wesleyan University, Middletown, Conn., by W. O. Atwater, professor of chemistry at the university and special agent in charge of the nutrition investigations of this Department, and E. B. Rosa, professor of physics at the university. The expenses entailed in conducting these investigations have been defrayed from funds for nutrition investigations of this Office and from funds contributed by the Storrs Experiment Station and Wesleyan University.

In a previous bulletin of this Office (No. 44) that portion of the respiration calorimeter which had to do more especially with the measurement of income and outgo of matter was described and experiments with man were reported, together with a brief history of the investigations. The present bulletin describes in detail that portion of the apparatus which has to do with the measurements of the income and outgo of energy. Experimental methods are described, as well as check experiments, in which the accuracy of the apparatus was tested with heat generated by an electric current and by burning alcohol in the respiration chamber. Two experiments with man in which the complete balance of income and outgo of matter and energy was determined are also reported. These investigations have extended over a number of years, but the results obtained are believed to amply compensate for the money and labor expended. An apparatus has been devised of such size that a man may spend a number of days in comparative comfort in the respiration chamber. Notwithstanding its size, the results obtained in the measurement of carbon dioxide, water, and heat are as accurate as those secured in investigations on a much smaller scale in which the usual laboratory methods are followed.

Particular mention should be made of the valuable assistance rendered by Messrs. A. W. Smith, A. P. Bryant, O. F. Tower, O. S. Blakeslee, and others, and especially the cooperation of Dr. F. G. Benedict, who has shared in the elaboration of the apparatus and methods as well as in the charge of the experiments.

This report is respectfully submitted with the recommendation that it be published as Bulletin No. 63 of this Office.

A. C. TRUE,
Director.

Hon. JAMES WILSON,
Secretary of Agriculture.

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DESCRIPTION OF A NEW RESPIRATION CALORIMETER AND EXPERIMENTS ON THE CONSERVATION OF ENERGY IN THE HUMAN BODY.

INTRODUCTION.

The purpose of this report is to describe a new respiration calorimeter and the test experiments made upon it, together with certain experiments made with it upon the conservation of energy in the human body.¹ The apparatus has been devised and the methods of experimenting have been elaborated for use in inquiries upon the transformation of matter and energy in the living organism. The ultimate purpose is the study of some of the fundamental laws of animal nutrition. The more immediate object, however, has been the study of the transformations of energy. This especial study is desirable for two purposes. One is the demonstration, if such be possible, that the law of the conservation of energy holds in the living organism. The other is the practical application of this law in gaining more definite knowledge of the ways in which the body is nourished and of the value and use of food. Preference has been given at the outset to the problem of the conservation of energy, not only because of its profound scientific interest, but also because of its fundamental importance in the study of the laws of nutrition.

In entering upon this research, to which the labor of many years must be given if results of the highest and most permanent value are to be sought, it was felt necessary to devise forms of apparatus and to elaborate methods of experimenting which should yield more detailed and accurate data than have been obtained hitherto.

That there is a lack of such data is clearly shown in a recent compilation of results obtained in one of the numerous lines of modern inquiry

¹An account of preliminary experiments with this apparatus was given in Bulletin No. 44 of this Office entitled, Report of Preliminary Investigations on the Metabolism of Nitrogen and Carbon in the Human Organism with a Respiration Calorimeter of Special Construction, by W. O. Atwater, C. D. Woods, and F. G. Benedict. In this publication, however, no account was given of those parts of the apparatus and experiments which have to do with the measurement of the income and outgo of energy, so that the experiments as reported were simply so-called respiration experiments in which the balance of nitrogen and carbon was determined. A preliminary account of the apparatus as a calorimeter, and of the experiments described in the present article, was given by the writers in the Connecticut Storrs Sta. Rpt. 1897, pp. 212-242.

regarding the nutrition of man and domestic animals in health and disease, namely, in experiments of the class in which the balance of income and outgo of one or more elements was determined.¹ This compilation includes the principal data of 3,661 experiments, of which 2,299 were made with man, 383 with cattle and horses, 928 with sheep, dogs, and other domestic quadrupeds, and 51 with poultry and doves. In 2,234 tests with man and 1,156 with animals the nitrogen balance was determined, and in 65 with man and 206 with animals the balance of carbon was determined. In 8 (with dogs), determinations were made of the balance of nitrogen and energy. In none was there a complete balance of the income and outgo of matter and energy. The earliest of these experiments was made in 1839; the large majority have been carried out within the last two decades or thereabouts. A few were made in the United States; a considerable number come from England, France, Switzerland, Italy, Scandinavia, and Russia; but more are from Germany than from any other country. The problems thus studied are extremely varied. In many cases the balance of income and outgo was determined in connection with investigations of experimental methods. In a large number of cases special questions were investigated, the balance of income and outgo being determined as a means of proof of the special problem, or for some similar reason. Numerous experiments have been made for the purpose of studying the source of muscular energy in the animal body, and other theoretical problems. That a vast amount of valuable information on these subjects is available can not be questioned. When, however, the investigations which have to do more especially with theoretical problems are examined in detail it is evident that the conclusions reached often contain more of partially attested theory than of well-established fact.

Recent progress in physics and chemistry has furnished improved means of carrying on such investigations as those alluded to, and has suggested additional lines of research. It is noticeable that there is a tendency to go over again the ground covered by some of the earlier investigations and to test the theories with the aid of improved methods. It is of the utmost importance, however, that investigators should cooperate in their work in order that unnecessary duplication may be avoided and that the best results may be obtained. Cooperation may be as successfully applied to scientific investigation as it is to business enterprises. This fact has been recognized in the organization of the nutrition investigations which are being carried out in different parts of the country under the auspices of this Department, with the cooperation of universities, colleges, experiment stations, social settlements, and other institutions. It applies no less truly, though in a somewhat different way, to the narrower study of the

¹A Digest of Metabolism Experiments in which the Balance of Income and Outgo was Determined, by W. O. Atwater and C. F. Langworthy, U. S. Dept. Agr., Office of Experiment Stations Bul. 45.

laws of animal nutrition. Not a few lines of research in this field have reached the point where even the best efforts of one or two individuals can not suffice, and an extensive combination of brain work, hand work, and material appliances is essential for obtaining the definite knowledge that is needed. To insure the best results experimental inquiries must be planned more philosophically and carried out with more thoroughness and in more detail than has generally been the case or, for that matter, has been possible hitherto in this country or abroad. This means that the research will be laborious and costly, but it will bring correspondingly valuable results. These considerations have been taken into account in planning the inquiry of which some of the results are described in this article. It will be proper to speak briefly of the chemical and physical principles involved in this special branch of physiological research before describing in detail the apparatus, the methods of experimenting, and the experiments themselves.

METABOLISM OF MATTER AND ENERGY.

In so far as its material phenomena are concerned, life consists in transformations of matter and energy. To these transformations the term metabolism is commonly and appropriately applied. The processes of metabolism are thus of two definite and closely allied kinds—the metabolism of matter, in which the changes are chemical, and that of energy, in which the changes are physical. It is commonly assumed that these two classes of change in living organisms, animal and vegetable, conform to the two fundamental laws of the conservation of matter and the conservation of energy.¹ To say that the chemical transformations in the body obey the first of these laws is simply to say that the body can neither create nor destroy matter, a principle which would hardly be disputed, since it is so abundantly confirmed in the inorganic world and there is no reason to question its application in animals and plants. In like manner it might be asserted that no living thing, animal or plant, can either create or destroy energy, and that whatever energy it receives it must either retain or give off in the same or other form without either increase or decrease; but this has not been demonstrated.

The principle of the conservation of matter in the animal organism has received experimental proof. While perhaps it was never seriously doubted, there have been discrepancies in the measurements of income and outgo, but improvements in experimental methods have greatly reduced such discrepancies.

With the conservation of energy in the living organism the case is different. The methods for determining the potential energy of organic

¹ Exactly this form of statement is not usual, but it seems simple and rational and certainly accords with the trend of later experimental research. See references to the subject in U. S. Dept. Agr., Office of Experiment Stations Bul. 21, p. 99.

substances are new. It is scarcely ten years since the bomb calorimeter, the first satisfactory apparatus for the purpose, was perfected, and its use in laboratories is not yet general. Comparatively few determinations of the heat of combustion of organic substances have been made. Even with the aid of such determinations the conservation of energy is not readily proven. We can analyze a mineral or vegetable substance and show that the weight of the elements or compounds obtained exactly equals the weight of the material used for the analysis, and thus demonstrate that in the chemical transformations the mass of matter has remained the same. But when we burn a substance in the calorimeter and measure the heat of combustion we can do no more than assume that the kinetic energy obtained as heat is equivalent to the potential energy originally belonging to the substance. We have no direct means of measuring initial potential energy and comparing the amount with that of the kinetic energy into which it has been transformed. The correctness of the conclusion that the kinetic energy found as heat is equivalent to the original potential energy of the substance depends not only upon the accuracy of the determination, but upon the assumption that the energy has been transformed without gain or loss—an assumption which we do not doubt, but which is incapable of absolute proof by any method now at our disposal. These difficulties, however, are not so serious as they appear. If the methods of determining the heats of combustion of organic substances are new, they seem to be reasonably accurate. If they are founded upon assumption, the foundation seems perfectly safe. If the results thus far obtained are few, they already serve their purpose and they are rapidly increasing in number.

The main difficulty in demonstrating that the law of the conservation of energy holds in the living body is in measuring the transformations of energy which take place therein. To prove that the law holds good we must know how much energy the body receives, how much it gives out, and how much it gains or loses of its accumulated store during a given time. In an experiment with a man, for instance, if we wish to demonstrate that the law of the conservation of energy obtains we must show that the income and outgo are equal. To show this equilibrium of energy we must know (1) the income of potential energy which the body receives in the food; (2) how much potential energy it gives off in the unburned material which it excretes (in urine, feces, etc.) and how much kinetic energy in the heat radiated from the body, and in the external muscular work done; and (3) the increase or decrease in the store of energy in the body during the experiment. If the body is warmer, or if it has a larger store of proteids or fat or glycogen or other substance containing potential energy at the end than at the beginning, it has stored energy during the period. If, on the other hand, it is colder, or if its store of substance containing potential energy is less at the end of the experiment than at the beginning, it has lost energy.

This gain or loss of energy by the body itself, the increase or diminution of its store during the experimental period, must be measured and allowed for if the experiment is to be accurate and reliable.

But even when we have measured accurately the income and outgo and the change of the store of energy as thus stated, we are not absolutely certain of our demonstration, although it is generally assumed that these factors are sufficient. It is not impossible that there may be other forms of energy in the outgo besides the heat radiated or otherwise given off from the body and the mechanical energy of external muscular work. It may be that the mental and nervous activities involve the expenditure of some form of physical energy which escapes our measurements.

Previous to the time of the experiments here reported no attempt had been made, so far as the writers are aware, to measure the total income and outgo of energy in the body of an animal or a man in such way as either to demonstrate the application of the law of the conservation of energy, or to show that it does not obtain. Partial measurements of the income and outgo of energy have been made from time to time, notably within the last five years. Such, for instance, are those of the experiments of Rubner¹ and the later ones of Studenski and other Russian investigators.²

The views of specialists as to whether the law of the conservation of energy actually applies in the living organism are somewhat conflicting. So far as the writers can judge, the larger number of chemists, physicists, and physiologists who have at all carefully considered the subject assume that the law does obtain, basing this supposition on the *a priori* ground that there is every reason to believe that it must hold in the organic world, as it has already been demonstrated to hold in the inorganic world. Not a few regard the experiments already made, notably those of Rubner just referred to, as implying very strongly, even if they do not strictly demonstrate, the application of this law in the animal body. Others, however, question this demonstration, and there are some physiologists, who, knowing from long experience the difficulties inherent in this kind of experimenting, the many sources of uncertainty and error, and the great amount of labor which is needed for reliable results, frankly avow their belief in the impracticability of any satisfactory proof that the law of the conservation of energy holds in the living organism.

These statements show the need of investigations which shall furnish experimental proof of the application of the law of the conservation of energy to the animal body. The experiments which have been undertaken for this purpose by the cooperation of the Department of

¹ *Ztschr. Biol.*, 30, pp. 119-138. See also U. S. Dept. Agr., Office of Experiment Stations Bul. 45, pp. 417-420.

² These Russian investigations are very briefly summarized in U. S. Dept. Agr., Office of Experiment Stations Bul. 45.

Agriculture, the Storrs Station and Wesleyan University, have in some respects followed the lines of earlier investigations. In other respects they have followed new lines. It has been found necessary to develop methods, devise apparatus, and make many investigations before the respiration calorimeter was perfected and the principal problem could be studied. It is not at all surprising that a period of more than five years should have elapsed between the beginning of the actual work and the time when the first results were ripe for publication. It is not claimed that the results here reported suffice for the complete verification of the law referred to. They do, however, in the judgment of the authors, render it extremely probable.

APPARATUS AND GENERAL PLAN OF THE EXPERIMENTS.

In order to determine the total income and outgo of matter the food, urine, feces, and gaseous excretory products must be measured and their composition ascertained. In experiments of the nature of those reported in this bulletin, it is usual to measure the income and outgo of matter in terms of the elements making up the food and excretory products. The income and outgo of energy may be most conveniently expressed in terms of heat. It is necessary to know the heat of combustion of the food and excretory products, the heat of combustion of the material gained or lost by the body, the heat radiated from the body, and the heat equivalent of the external muscular work performed. The following statement shows the determinations which were actually made in obtaining the balance of income and outgo of matter and energy:

INCOME.

Matter.—Food and drink: Elements, C, H, N; compounds, water, protein ($N \times 6.25$); fats (other extract); carbohydrates (estimated by difference); mineral salts (ash).

Energy.—Potential energy of food and drink as shown by heats of combustion; heat of food and drink as inferred from temperature and specific heats.

OUTGO.

Matter.—Feces: Same elements and compounds as in the food and drink. Urine: Elements, as in food and drink; compounds, water, and in some instances urea and other substances. Respiratory products: Elements C, H; compounds, carbon dioxide and water.

Energy.—Potential energy of excretory products as shown by heats of combustion; heat and heat equivalent of external muscular work.

For an ideal experiment other determinations would be desirable, but it is believed that those actually made are sufficient.¹

The determination of the above factors requires a special apparatus, capable of measuring the inspired and respired air and the heat produced by the body. This has been called a respiration calorimeter.

The name "respiration calorimeter" is suggested by the fact that it

¹ This subject is discussed at considerable length in U. S. Dept. Agr., Office of Experiment Stations Bul. 44, pp. 7, 8.

is essentially a respiration apparatus with appliances for calorimetric measurements. As a respiration apparatus it is similar in principle to that of Pettenkofer. As an instrument for measuring heat it is essentially a constant temperature calorimeter. The heat is absorbed and carried away by a current of water as rapidly as it is generated in the chamber. It is therefore a water calorimeter. The arrangements for the measurement of both the respiratory products and the heat given off from the body differ in important respects from those of any other apparatus with which we are familiar.

The essential features of the apparatus are:

(1) A chamber in which the subject of the experiment, a man, lives, eats, drinks, sleeps, and works during a period of several days and nights. The chamber is furnished with a folding chair, table, and bed.

(2) Arrangements for ventilation by a current of air which is drawn from out of doors and passes through the chamber. The volume of this air current is measured and its temperature is so regulated as to be the same on entering the chamber as upon leaving. Samples for analysis, taken before it enters and after it leaves the chamber, give data showing the amount of carbon dioxid and water given off from the body through the lungs and skin.

(3) Arrangements for passing food and drink into the chamber and removing the solid and liquid excreta. These materials are analyzed and give data for calculating the income and outgo of nitrogen, and of sulphur, phosphorus, chlorin, and metallic elements if these are determined. Taken in connection with the determinations of carbon dioxid and water in the respiratory products, they show the income and outgo of carbon and hydrogen. The analyses of the food, and of the solid and liquid excreta, enable us to determine the so-called digestibility of the food, i. e., the proportions of nutrients actually made available.

(4) Arrangements for measuring the heat given off from the body of the man in the chamber and the heat equivalent of the external muscular work. The heat given off is carried away by a current of cold water which passes through a series of pipes inside the chamber. By regulating the temperature of this water current as it enters, and also its rate of flow, it is possible to carry away the heat just as fast as it is generated, and thus maintain a constant temperature inside the chamber. The amount of the outgoing water and its increase in temperature are measured, thus determining the amount of heat carried away.

In order that the heat taken up by the absorbers and carried out by the water current shall represent exactly the amount given off from the man's body or otherwise produced in the chamber, it is necessary to provide that there shall be no passage of heat through the walls, or rather, that the small quantities that may pass in and out shall exactly counterbalance each other, and that the ventilating current of air shall leave the chamber at the same temperature as it enters, so that it shall carry out neither more nor less heat than it brings in. The excess

of water vapor in the air leaving the chamber over that in the air entering represents water given off from the body of the subject, and the heat required to vaporize it must be added to the heat carried off by the current of water to obtain a measure of the total heat given off by the subject.

In the actual experiments the man remains for several days and nights (generally four days and five nights) in the chamber. The food and drink are passed in and the feces and urine removed at regular intervals. The diet is decided by the special question which is being studied, but is made agreeable to the subject of the experiment.

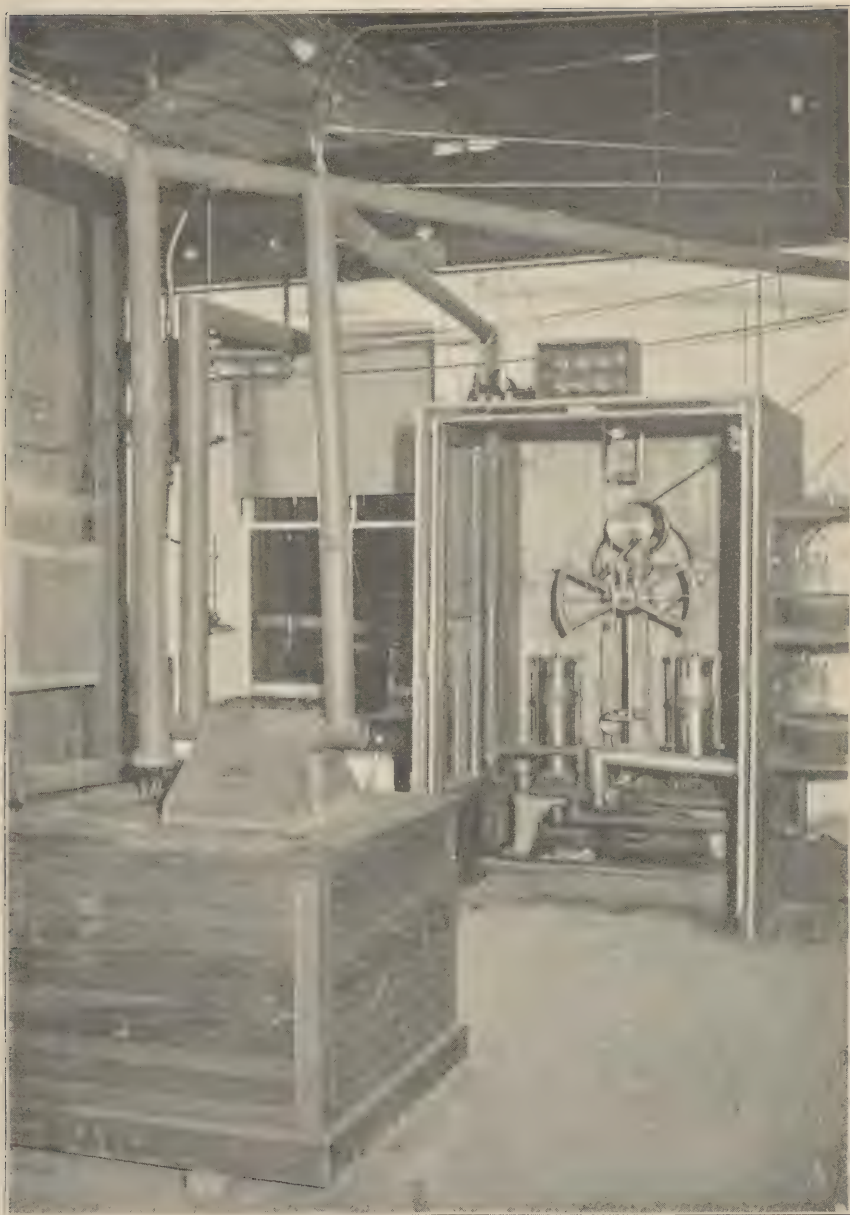
In some of the experiments the man had as little muscular exercise as practicable. In these so-called "rest experiments" no attempt was made to measure the muscular work. In others, so-called "work experiments," the amount of work done was measured by a specially devised ergometer, consisting of a stationary bicycle which was belted to a small dynamo. The electric current generated passed through an incandescent lamp inside the chamber, where its energy was transformed into heat. The strength of current and voltage was determined by instruments outside the calorimeter. The heat equivalent of the muscular work done was thus added to and measured with the heat given off from the body. The duration of the work and the amount of the electric current generated gave data for the computation of the amount of work performed.

The men who have served as subjects of the experiments have not found their sojourn in the chamber disagreeable nor have they suffered any special inconvenience. The experiments are, however, very laborious, and require not only the services of trained observers day and night for the chemical and physical determinations, but also a considerable amount of painstaking work in preparing the food, taking care of the excreta, and attending to the numerous details before, during, and after the experiment.

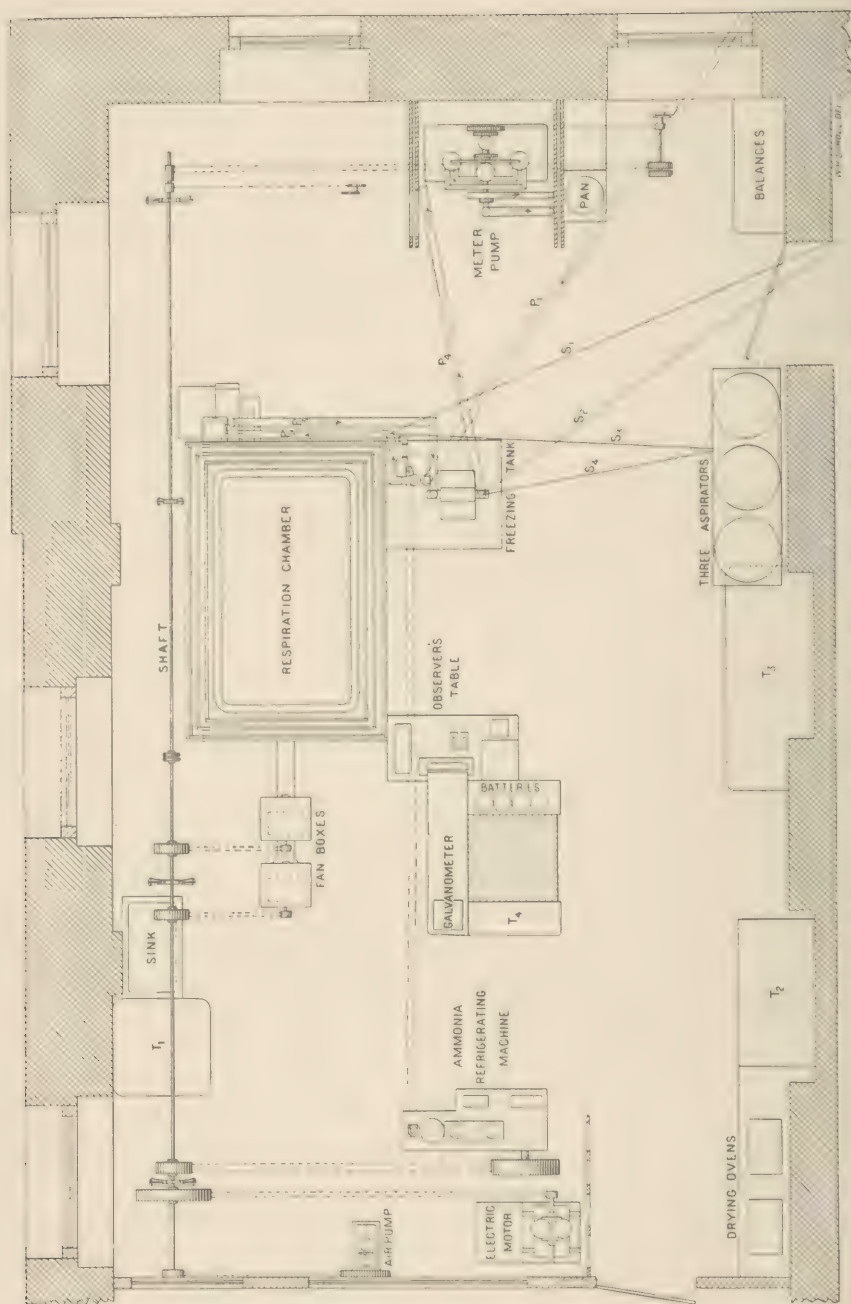
DESCRIPTION OF THE APPARATUS.

A general idea of the apparatus can be had from Pl. I (frontispiece) taken from a photograph. This gives a general view of the principal parts of the apparatus, which stands in a basement room of the Orange Judd Hall of Natural Science, at Wesleyan University. In the center is the large chamber, which is surrounded by a sheathing of wood. At the end of the chamber, on the right, is shown a door, which serves also as a window. At the right of the window and just below it are the arrangements for cooling and measuring the current of water which brings away the heat from the interior of the chamber. At the left, in front of the large brick pillar, is a table¹ at which an observer sits to record the temperature of the interior of the apparatus and of

¹This table has lately been moved to a position just in front of the apparatus. This in no wise modifies the method of experimenting.



THE FREEZING TANK AND METER PUMP.



GROUND PLAN OF RESPIRATION CALORIMETER ROOM WITH APPARATUS AND ACCESSORIES.

the currents of air and water, the temperature being measured electrically. Behind the brick pillar is an ammonia refrigerating machine, not shown in the picture. Its purpose is to cool the solution of calcium chlorid which is contained in a large tank in the center foreground. This tank (Pl. II, and fig. 10, p. 30) is inclosed within a double-walled wooden casing. The liquid ammonia is evaporated in the coiled iron pipe, shown in fig. 10, p. 30. The ventilating current of air, before it enters the chamber, is passed through the coppercon denser A, which is immersed in the calcium chlorid solution in the right-hand corner of this tank, and thus cooled to a temperature of from -19° to -22° C. At this very low temperature nearly all of the water is removed from the air, so that it enters the chamber quite dry. Just before entering at the right of the glass door it is warmed to the temperature of the interior of the chamber. On coming out it passes through a second condenser, consisting of a pair of copper cylinders B, C, in the cold brine in the tank, and thus the larger part of the water which has been imparted to it by the respiration of the man inside the chamber is frozen and deposited. By means of valves contained in the valve boxes above the cylinders, the air current may be diverted to a second pair of cooling cylinders D, E. The first pair may then be removed and the deposited moisture determined by the increase in weight. The air pump is shown at the right of Pl. II.

The disposition of the various parts of the apparatus is further shown in the ground plan of the room (Pl. III). On the north and east sides of the room the massive stone walls of the building appear in section, interrupted by five large windows. The window of the respiration chamber opens toward the east, so that the interior of the chamber is lighted from the two windows in the northeast corner of the room. At the west end of the room stands a 2-horsepower electric motor, belted to the driving pulley of a line shaft extending the entire length of the room. From this shaft power is taken to drive the ammonia refrigerating machine, the fans contained in the two fan boxes which circulate the air in the space surrounding the respiration chamber, and the meter pump which propels and measures the ventilating air current. A compression air pump is also driven from the shaft. This provides the compressed air which operates the valves of the meter pump. The air current passes from out of doors through the pipe P_1 into the refrigerating tank where the greater portion of its moisture is deposited, and thence by the pipe P_2 to the respiration chamber (fig. 2), after being warmed to the temperature of the latter. From the respiration chamber the air passes through the pipe P_3 to the refrigerating tank, where its moisture is again deposited for the most part, and thence to the meter pump through P_4 . Here the pump records the volume of air and delivers every fiftieth cylinderful to the pans for analysis for carbon dioxid and residual moisture. Through small pipes S_3 , S_1 , samples for analysis of the dried air of the pipes P_2 , P_4 are drawn by the aspirators shown on the south side of the room; and through the pipes S_1 and

S_2 other similar samples are drawn off by aspirators in an adjoining room for duplicate analyses. The details of these operations will be given further on. On the north side of the pier near the middle of the room, and attached to the pier, is the galvanometer, used for measuring electrically temperatures and differences of temperature; and on the observer's tables are located Wheatstone bridges, keys, and resistances used in the measurement and regulation of temperatures, as hereafter described. Tables T_1 , T_2 , T_3 and other appliances afford facilities for part of the chemical work done in connection with the experiment, but most of the chemical work is done in other portions of the building.

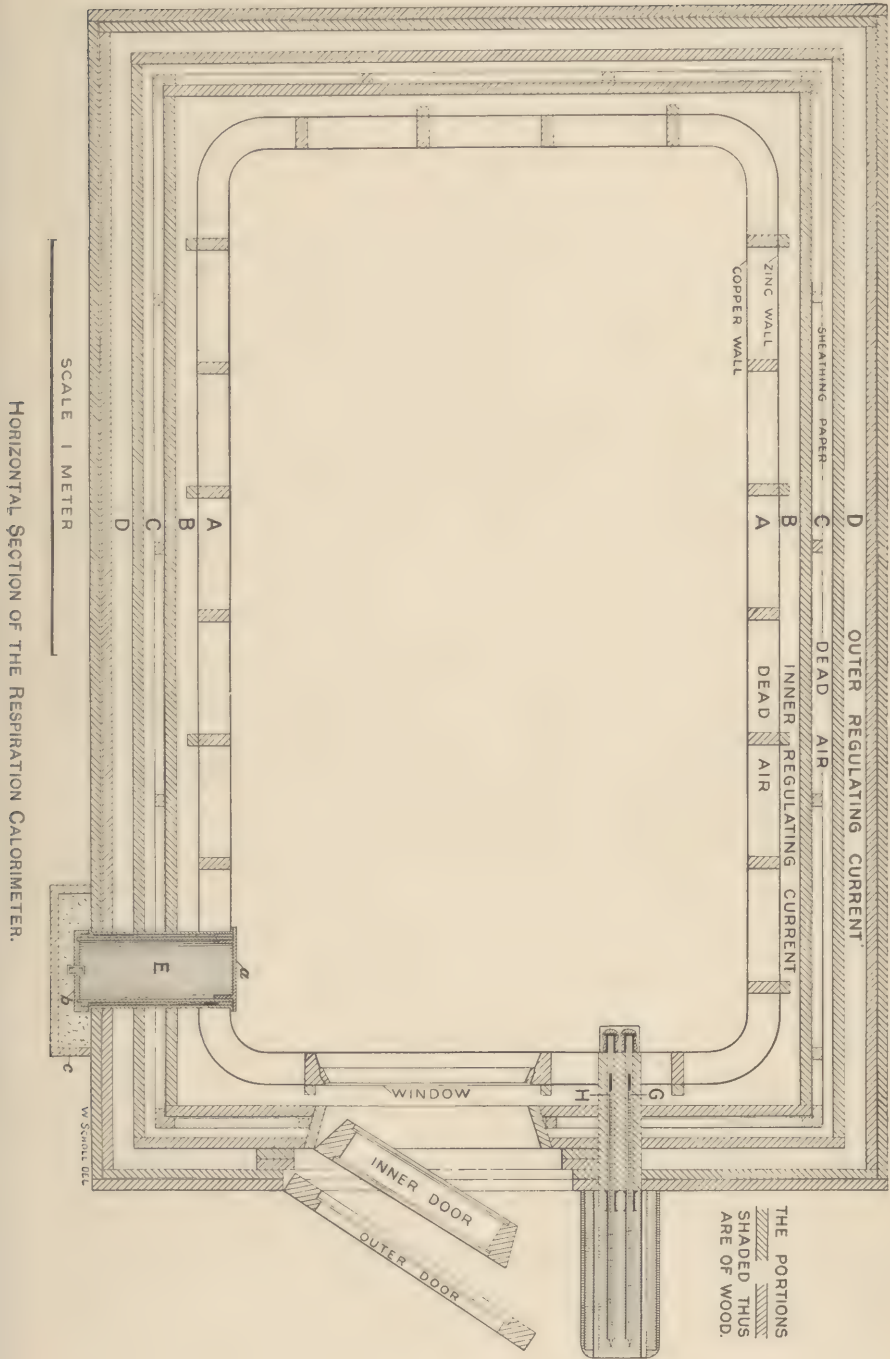
ARRANGEMENTS FOR PREVENTING A GAIN OR LOSS OF HEAT THROUGH THE WALLS OF THE CALORIMETER.

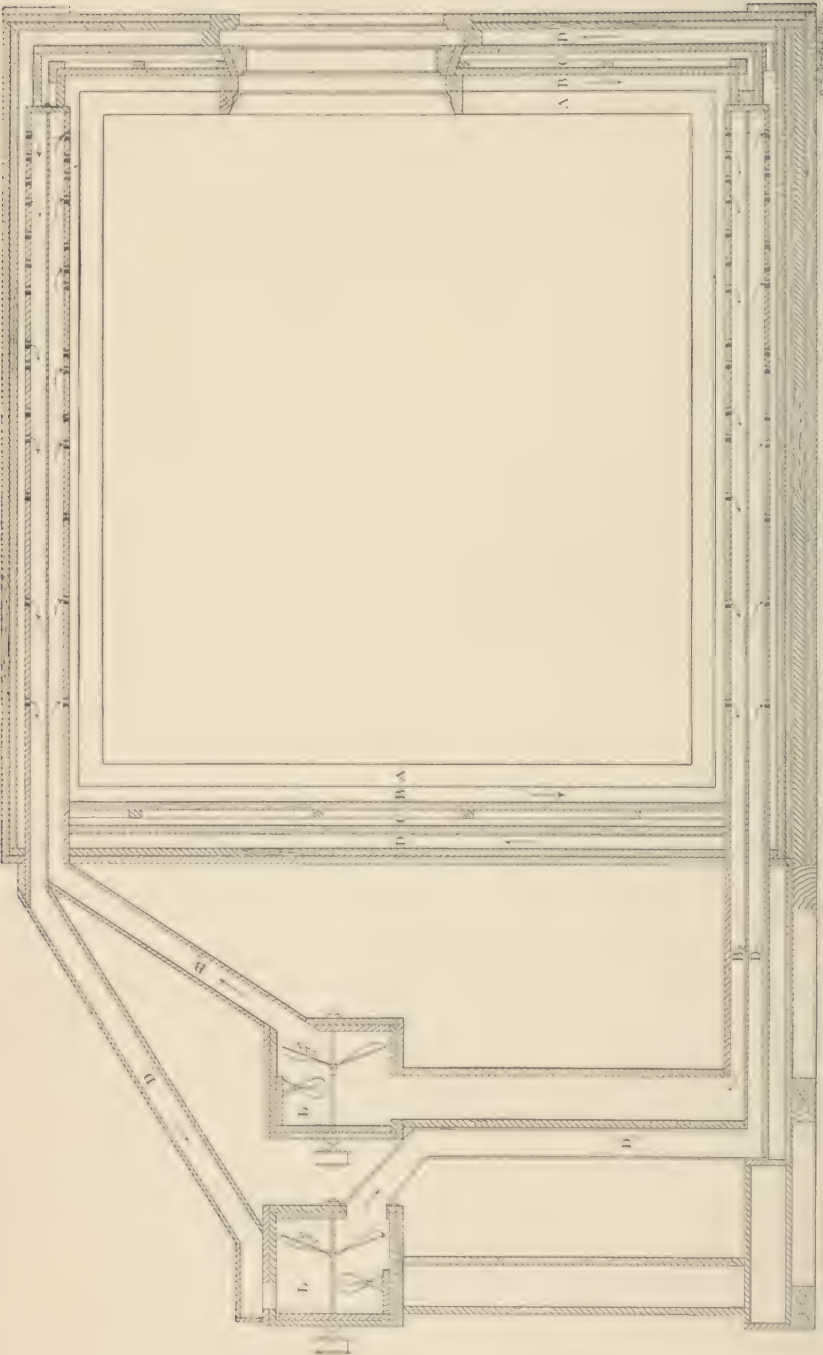
CONSTRUCTION OF THE CALORIMETER.

The construction of the calorimeter is shown in horizontal section in Pl. IV. The inner chamber is practically an apartment with double walls of metal. The inner of the two metal walls is of sheet copper, and incloses a space 2.15 meters (7 feet) long, 1.92 meters (6 feet 4 inches) high, and 1.22 meters (4 feet) wide, the corners being rounded. Copper was chosen because it can be obtained in large sheets, can take a high polish and so the more fully reflect radiant energy, is a good conductor of heat and thereby tends to equalize local differences of temperature, and has a rather small specific heat. A window in one end, 70 centimeters high by 49 centimeters wide, serves also the purpose of a door. During an experiment, however, the door is sealed and a circular opening, E , which has tightly fitting caps a , b , both inside and outside, is used for communication with the interior. Outside is a box, c , filled with nonconducting material to prevent the passage of heat through E . The seams are soldered and the chamber is air-tight when the door and other openings are sealed. The outer metal wall is of zinc, which is less expensive than copper, and serves the purpose sufficiently well. Between the two walls is an air space, A , of 7.6 centimeters (3 inches). In this stands a wooden framework to which the two metal walls are securely attached.

In order to protect the calorimeter from the fluctuations of temperature of the basement room in which it stands it is inclosed within three concentric walls of wood. Through each of these is an opening corresponding to the window in the wall of the calorimeter proper. These openings are closed by tightly fitting glass doors, hung on hinges.

Near these doors are shown the pipes through which the water enters and leaves the calorimeter. Its temperature on entering is measured by the mercury thermometer, G ; and as it leaves, by a similar thermometer, H . Between the zinc wall and the innermost wooden wall is a 5 centimeter (2-inch) air space, B ; between this wall and the next is a third air space, C , of 5 centimeters (2 inches); and, finally, between





VERTICAL SECTION OF THE RESPIRATION CALORIMETER.

this wall and the outer one is a fourth air space, D, of 5 centimeters (2 inches). The wooden walls are made of matched pine, covered with building paper, and the outer one is double, with paper between. Of these four air spaces A and C are "dead" air spaces, while the air in the spaces B and D can be kept in constant circulation by means of rotary fans driven by power. Each of the air spaces B and D is continuous around the sides and over the top and bottom, and each communicates with its fan box in the rear by means of one passage extending from the top of the air space to the top of its fan box, and another from the bottom of the air space to the bottom of its fan box. Thus the air may be kept in constant circulation through these two air spaces, and by heating or cooling this moving air the temperature of the corresponding space may be raised or lowered. We may also look upon the moving strata of air as shields, guarding the interior space occupied by the calorimeter from changes in temperature without. A vertical section of the calorimeter is shown in Pl. V. The walls at the top and bottom are constructed like those of the sides, but as this section is taken through the center of the chamber it shows the flues for the regulating air currents. The air from the space B is drawn into the upper part of the bottom flue, as indicated by the arrows, and by means of the inner fan is driven into the lower part of the flue at the top. Openings along this flue allow the air to flow out over the top of the calorimeter, and thence down around the four sides to the bottom and so back to the fan again.

Similarly the air in the space D is kept in circulation by the fan in the outer fan box. The circulation in this space is in the opposite direction from that in B; that is, the air is taken from the top and driven in at the bottom. As the upper part of the room is usually much warmer than the floor, this arrangement for the outer circulating air tends to equalize the difference of temperature by drawing off the hot air from the top and driving it in at the bottom. At the front are shown the glass window and doors as closed.

THE THERMO-ELECTRIC ELEMENTS.

In order to determine whether the inner or outer metal wall of the calorimeter is the warmer—that is, in order to know whether to heat or to cool the air space B—we use a large number of pairs (304) of thermo-electric junctions, distributed over the four sides, top, and bottom of the calorimeter, one-half of the junctions (the iron-German-silver) being in close thermal contact with the copper wall and the other half (the German-silver-iron) with the zinc wall. One of these elements is shown in fig. 1, where C_1 is a copper cartridge shell or cap, soldered to the copper wall, and maintaining the inclosed thermo-electric junction at the same temperature as the copper wall, and C_2 is a similar cap soldered to the zinc wall. There being copper leads connecting the several pairs,

there are two junctions (copper-iron and German-silver-copper) in the outer cap; but these are thermo-electrically equivalent to one German-silver-iron junction. In reality there are four pairs of junctions in each group instead of a single pair as shown in the figure. These thermo-electric elements are made of silk-covered iron and German-silver wire No. 20. They are all in series, and are joined to a sensitive D'Arsonval galvanometer. The galvanometer is quick and deadbeat, and readings may be taken rapidly. If the copper wall is on the whole warmer than the zinc, the electromotive forces due to the junctions in contact with it overpower those due to the junctions in contact with the zinc wall and a current flows through the galvanometer, proportional in amount to the difference of temperature of the walls, and produces a deflection

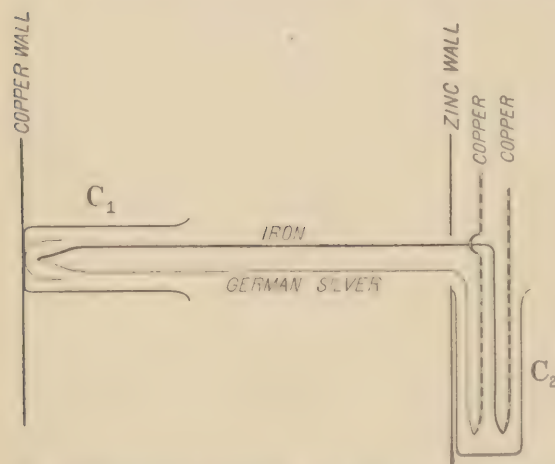


FIG. 1.—Thermo-electric junctions. C_1 and C_2 are ordinary copper cartridge shells soldered to the copper and zinc walls, respectively, and contain the junctions of the thermo-electric elements. Only one pair of junctions is shown in the figure, but there are really four such pairs in each group. The junctions are electrically insulated from the walls of the calorimeter, but in the best possible thermal contact.

to the right. It is then necessary to warm the space B, which raises the temperature of the zinc wall, and the deflection will be reduced. If the deflection is to the left, the space B is cooled until the deflection is zero. A deflection of 1 division on the scale represents a difference in temperature between copper and zinc of about 0.007°C . An experienced observer can ordinarily keep the deflection within one or two divisions, and by taking frequent readings at regular intervals

the + and - deflections are separately summed up and made to cancel each other as the experiment proceeds, and hence no "cooling correction" is necessary.

Of course the deflection of the galvanometer is due to the algebraic sum of all the electromotive forces at the 304 pairs of elements. At some places the copper may be warmer and at other places colder than the zinc, and the galvanometer indicates an average difference. In order that this average may be the more reliable the elements have been spaced as nearly uniformly as possible over the entire surface. There are 76 groups of elements of 4 pairs each: Of these 76 groups 11 are on the top, 11 on the bottom, 22 on the upper part of the four sides (over two-fifths of the whole area), and 32 on the lower part of the four sides (covering the remaining three-fifths of the area). Thus

the elements are joined up in four sections, designated respectively as top, upper, lower, and bottom, and each section can be joined to the galvanometer separately. In practice, therefore, we can determine whether to heat or cool any of the four sections, top, upper, lower, or bottom, in order that the deflection shall always be small for each section, and that the total deflection for all shall be zero. This secures a more perfect balance than could be had if only the total deflection were zero; for then an appreciable quantity of heat might be flowing in at the top and out at the bottom and the two quantities not exactly balancing each other.

There are 26 pairs of thermo-electric elements set in the wooden wall between the air spaces B and D, one set of junctions extending into the air space B and the other into D. These elements indicate the difference of temperature between B and D, and indicate when D must be heated or cooled to keep it nearly at the temperature of B.

HEATING AND COOLING DEVICES.

In order to be able to heat or to cool any of the four sections of the air space B separately, a system of German-silver wires for heating and of iron pipes for cooling are arranged in this space, between the inner wooden wall and the zinc wall. German-silver wire No. 30 was stretched horizontally around the calorimeter, being supported and insulated by passing it through glass tubes set into vertical wooden strips which are attached to the zinc wall. The wire was divided into four sections corresponding to the four sections of the thermo-electric elements and the ends brought out so that an electric current could be passed through any of them at will, the strength of the current being regulated by variable resistances. In a similar manner $\frac{1}{4}$ -inch (6 millimeters) iron pipes are arranged in four sections so that by opening a valve water from the city service can be passed through any of the pipes, to cool the surrounding space; when the water is shut off, a vent in each of the valves allows the pipes to drain. When only slight cooling is needed, the water may be allowed to flow only a few seconds at a time. In this manner the temperature of the air space can be perfectly controlled, and when the temperature within the calorimeter remains constant, as when heat is being generated at a uniform rate, the deflection can usually be kept within 1 division, which means an average difference of temperature between copper and zinc of less than 0.01°C .

Inasmuch as the temperature of the room is always lower near the floor than near the ceiling, the air circulating through the space D is warmed by passing over electric lamps or through a pipe heated by a Bunsen burner and made to enter at the bottom of the calorimeter. This tends to equalize the temperature between the top and the bottom, and guided by the indications of the second set of thermo electric junctions, the air in D is kept nearly at the temperature of that in B.

Thus the space B is perfectly protected from changes of temperature without, and it is possible to keep its temperature almost the same as that within the chamber.

THE OBSERVER'S TABLE.

The terminals of the thermo-electric circuits and of the galvanometer are brought to the observer's table (Pl. I). The galvanometer stands on a shelf attached to a brick pier, about 2 meters beyond the table, and the galvanometer scale is directly over the table (Pl. III, p. 15), being also attached to the pier. A 4-point switch, N, joins the galvanometer to the several thermo-electric circuits in succession. If the key is on the first point, the thermo-electric circuit of the copper-zinc walls, designated as No. 1, is joined to the galvanometer, and the deflection indicates their difference of temperature, as already explained. An auxiliary switch, M, throws into the circuit any of the four sections separately, or all together when desired.

The 26 pairs of thermo-electric elements, designated as circuit No. 2, set in the wooden wall between the spaces B and D, are joined in series, and the terminals are brought out to the switch N, and joined to the galvanometer when the key is on the second contact. The galvanometer then indicates whether the space D is warmer or colder than B, and thus shows whether to heat or to cool the air flowing through it. If the temperature of the room is not very different from that of the calorimeter it is not necessary to heat or cool the air in D. But if the room is much colder than the respiration chamber, as is often the case at night when there is no steam in the radiators in the room, then by heating the air of D before it enters at the bottom it protects the space B from outside influence. The temperature of the room not infrequently falls to 15° or 13° C., while that of the respiration chamber is maintained constant, usually at about 22° C.

When the key is on the third contact the galvanometer is short circuited, and when on the fourth the thermo-electric junctions, designated as circuit No. 4, in the ventilating air current, hereafter to be described, are joined to the galvanometer.

A bank of incandescent lamps, LL, is divided into five groups of 7 lamps each. Each of four groups is in series with one section of the German-silver heating coils already referred to, and which are wound around the calorimeter in the air space B. For example, the first section is in series with that section of the coil distributed over the top of the calorimeter, and the current is regulated by varying the number of lamps in series. Any one or more lamps can be cut out of circuit by a short-circuiting key. The lamps have different resistances, and by suitable combinations any desired current may be obtained, the source of current being the 220-volt-power circuit from which the electric motor is driven.

The fifth section of lamps is in series with an incandescent lamp

placed in the pipe through which the ventilating current of air enters the respiration chamber, and by regulating the current through it, the temperature of the air as it enters is maintained the same as that of the air leaving.

Bridge No. 6 is a Wheatstone bridge, by means of which the difference of temperature of the stream of water as it enters and leaves the

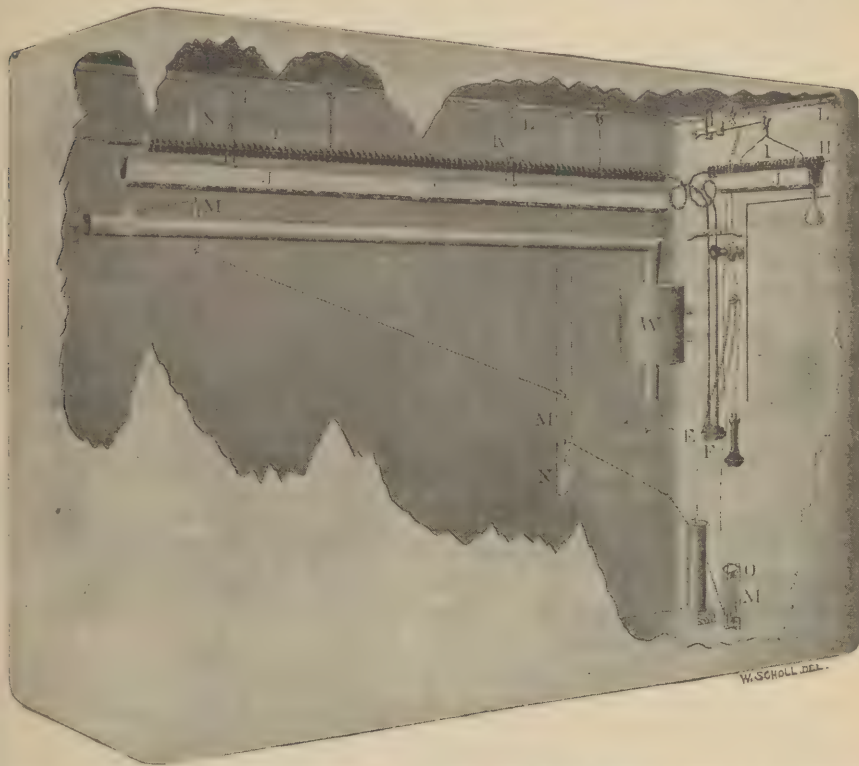


FIG. 2.—Interior of respiration chamber. This is the view which would be secured by breaking away a portion of one side and end of the interior copper wall of the respiration chamber. The ventilating air enters the chamber through the bottom of W, leaving from the rear of the chamber through the long tube connected with the upper end of W. The copper tubes H, I, strung with copper disks I, I, constitute the absorbers through which flows the water current which carries away the heat generated in the chamber. J, J are the copper troughs for collecting the drip from the absorbers. M, M, M are electrical thermometers which show the temperature of the air in the chamber; N, N those which show the temperature of the copper wall.

calorimeter is measured, and bridge No. 5 is a similar Wheatstone bridge for determining the temperature of the respiration chamber. These bridges will be described later.

APPARATUS AND METHOD FOR MEASURING THE HEAT.

THE WATER SYSTEM.

Having arranged the calorimeter so that no heat can escape or enter through its walls, it remains to carry away and measure the heat generated. This is done by a stream of water flowing through a copper

"absorber" (III, fig. 2). A copper pipe of 6 millimeters ($\frac{1}{4}$ inch) bore was bent into a rectangle 90 centimeters by 182 centimeters (3 feet by 6 feet). In order to increase the absorbing area of the pipe, one thousand disks II, 5 centimeters (2 inches) in diameter and with a 1 centimeter ($\frac{3}{8}$ inch) hole in the center, stamped out of sheet copper, were slipped over the pipe like beads on a string, and soldered 6 millimeters ($\frac{1}{4}$ inch) apart. The pipe and disks were then painted black. This absorber is suspended about 25 centimeters (10 inches) below the ceiling of the calorimeter, and 15 centimeters (6 inches) from the sides and ends. Water enters the calorimeter from the coolers through a pipe, E (figs. 2 and 3), containing a mercury thermometer, G (fig. 3), and after flowing through the absorber leaves through a second pipe, F, near to and parallel with the first, containing a second thermometer, H. These

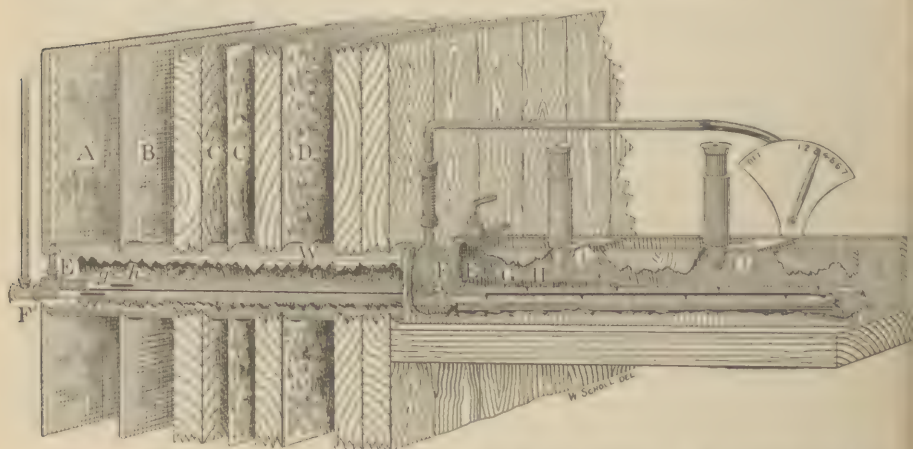


Fig. 3. Section through walls of the calorimeter, showing thermometers. A is the copper and B the zinc wall of the calorimeter chamber. C and D are the inclosing walls of wood and paper. The long thermometers G, H, extend into the two pipes E, F, through which the current of water enters and leaves the calorimeter. Readings are taken by means of the microscopes, the scale being illuminated by small electric lamps. The rate of flow of water is regulated by a valve with an index moving over a graduated scale.

two water pipes pass through holes in a cylindrical block of wood. The bulbs of the thermometers are at a point, *g*, *h* (fig. 3), midway between the zinc and the copper walls. Hence one gives the temperature of the water just as it enters the respiration chamber and the other its temperature as it leaves. The thermometers are 60 centimeters (24 inches) in length, and are graduated from 0° to 30° C., in twentieths of a degree, and read to hundredths of a degree. They have been carefully compared with our standards. These thermometers are read by microscopes mounted as shown in fig. 3, the thread of mercury being illuminated by small electric lamps. Their difference of temperature gives a measure of the heat absorbed within the calorimeter per gram of water.

In order to regulate the temperature of the ingoing water, and espe-

cially to have it as low as required, it is passed through a cooler. This, as shown in fig. 4, consists of a pair of closed copper cylinders submerged in a bath of cold calcium chlorid. The temperature of this bath is kept at the desired point by pumping in cold calcium chlorid solution from the large refrigerating tank as often as necessary. The water to be cooled enters the first cooler, being carried to the bottom where the warm water prevents the formation of ice. This water being partially cooled enters the second cooler, being carried to the bottom as in the first one. Here it is cooled still further before going to the

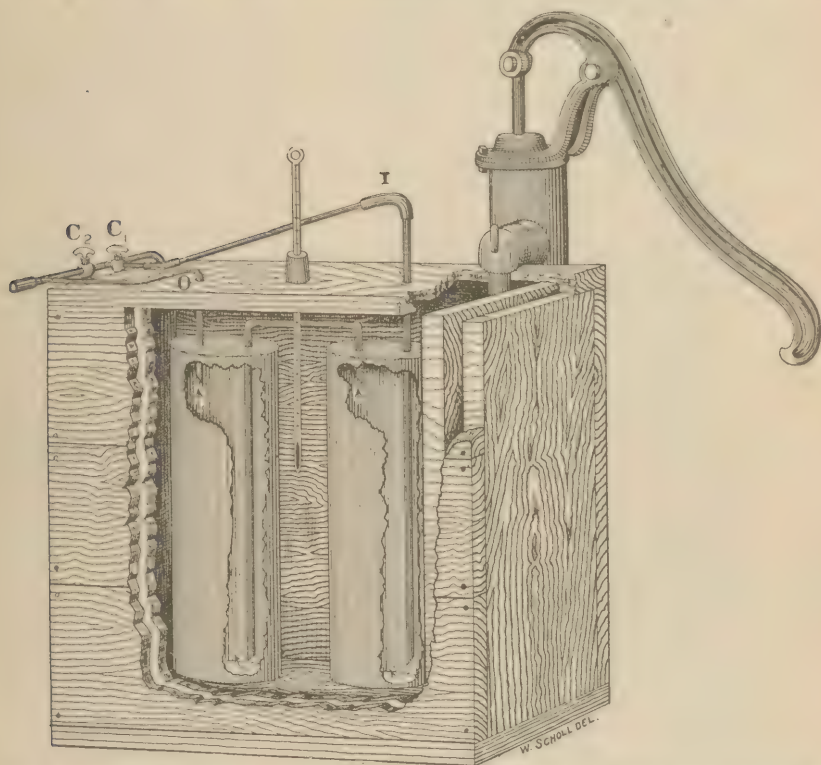


FIG. 4.—Apparatus for cooling incoming current of water. The two cylinders shown within the tank are surrounded by a solution of cold calcium chlorid drawn from the large refrigerating tank by means of the pump shown.

absorbers. By this means the ingoing water can be brought as low as 2°C . if desired, and any higher temperature can be obtained either by varying the temperature of the bath or by mixing the cold water with warmer taken directly from the supply. At the top of the room is a tank which is kept full and overflowing by a stream of water from the city service. From this tank is taken the water which flows through the absorbers. Having thus a constant head, the rate of flow of water through the absorbing pipes is uniform. A regulating valve with a pointer moving over a graduated arc (fig. 3) enables one to vary the rate of flow within wide limits.

THE WATER METER.

The water is received in a special form of water meter (fig. 5), having a capacity of 10 kilograms. The water which has flowed through the

absorbers runs into the small cup A, which is divided by a vertical partition through the center and reaching from the bottom about half-way to the top. On either side of this partition are small tubes leading from the bottom of the cup A to the cylinders B and C. When the water running into A falls on one side of the partition it will run down the tube to the corresponding cylinder, which will be filling up. As the level of the water rises it will finally be as high as the top of the partition in the little cup A, when no more water will enter, but will overflow and run into the other cylinder. The first cylinder now contains just 10 kilograms of water.

In the narrow neck of the cylinder is a float, F, in the form of a test tube. This is hung from the end of a spring, and as the rising water lifts the float the spring comes in contact with the point H and closes the circuit of an electric alarm bell which continues to ring until the siphon S is started and

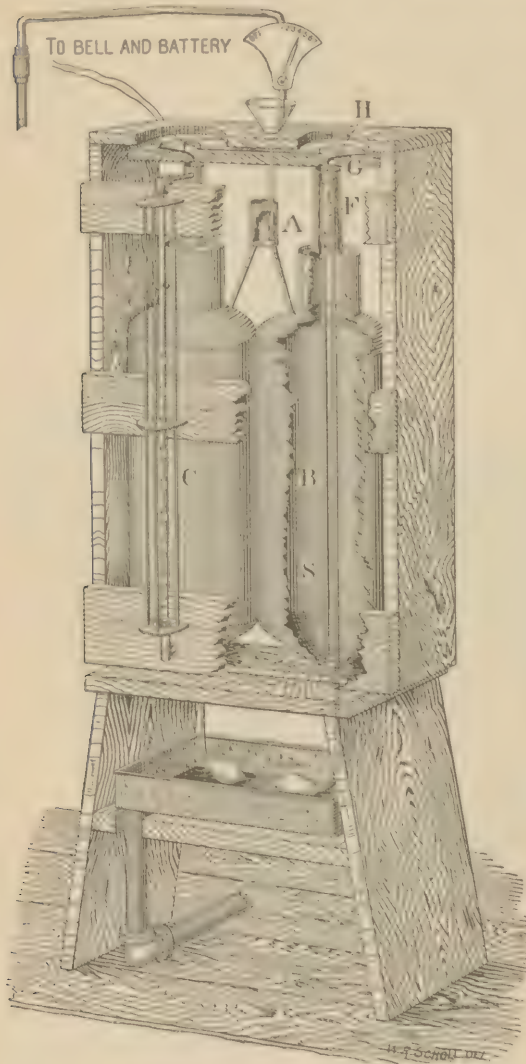


FIG. 5.—Water meter. The stream of water which carries away the heat generated in the respiration chamber flows into one of the cylinders B, C, until it is filled, when the stream is diverted automatically by the apparatus A, to the other cylinder. The first is emptied by means of the siphon S. The siphon is operated by the attendant whose attention is called by an electric bell which begins to ring as soon as the cylinder is filled, and continues ringing until the siphon is started.

the cylinder begins to empty. After the siphon is started it will draw all the water from the cylinder down to a certain level without

any further attention. The stream of water is diverted to the other side of the cup A by the operator before the siphon is started. Record is made at the instant the meter is filled, and the interval between successive records gives the period for the corresponding 10 kilograms of water. Thus the product of the average difference of temperature between the ingoing and outgoing water by 10 gives the number of calories of heat brought away during the given period.

DETERMINING THE INCREASE OF TEMPERATURE OF THE WATER.

As a check upon the thermometer readings, and in order to avoid too frequent readings of the thermometers, two coils of copper wire are sealed in thin copper tubes and inserted in the water pipes near the bulbs of the thermometers. They are joined to two comparison coils on the slide-wire Wheatstone bridge No. 6 (Pl. VI), graduated so that readings on the scale give differences of temperature of the water in the pipes, 1 millimeter being 0.01°C . Readings on this bridge are usually taken every two minutes during an experiment, and careful readings on the mercury thermometers are taken occasionally for calibration purposes. This bridge is equivalent to what is generally known as a platinum thermometer, but inasmuch as copper coils are used instead of platinum, it is here called a "copper thermometer." The resistance of copper increases with its temperature, and hence the difference of temperature of two coils of wire may be accurately measured by determining their resistances.

The principle employed for the measurement of these resistances is, as just stated, that of the Wheatstone bridge, illustrated in fig. 6. The four arms are A, B, C + c, D + d. The battery is joined at B₁ and B₂, the galvanometer at G₁ and G₂. If A and B represent the proportional arms of the bridge, which are here equal, C and D the two copper coils in the water pipes, and c + d the slide wire of the bridge, then for no current through the galvanometer the following proportions must be true:

$$A : B :: C + c : D + d.$$

Suppose now the coil D is warmed so that its resistance is increased. To keep the bridge still balanced, B₂ must be moved along the slide wire reducing d, and, at the same time, increasing c, until the bridge

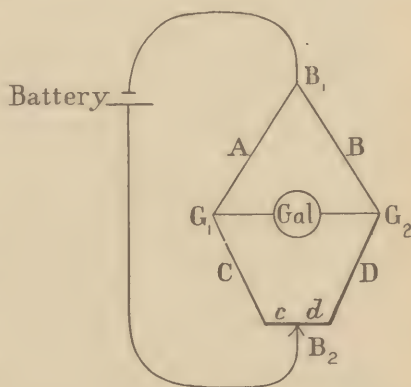


FIG. 6.—Diagram illustrating use of copper thermometer. This is a Wheatstone bridge in which A and B are two equal comparison coils, C is a fixed resistance, D is the resistance coil in the calorimeter, and c and d are the two parts of the straight wire on the bridges shown in Pl. VI.

is again balanced. By properly graduating the slide-wire scale the position of B will show directly the difference in temperature between the coils C and D; and these coils of fine insulated copper wire, inclosed in very thin copper tubes, quickly take up the temperature of the water by which they are surrounded.

Referring now to Pl. VI, the connection of bridge No. 6 will be readily seen. The parts are lettered the same as in fig. 6. In addition are the small coils c' , c'' , c''' . The length of the bridge wire corresponds to a difference of temperature of 5° in the coils C, D. If the difference increases above this the coil c' is added to C, so that the slider instead of being at " 5 " will be at " 0 ", and then differences of temperature between 5° C. and 10° C. can be measured. In the same way, when the difference reaches 10° C., c'' is added to $C+c'$, and " 0 " then corresponds to 10° C. The connections are made and changed by means of a heavy link dipping into mercury cups. The scale is 500 millimeters in length, and hence the position of the slider can easily be read off in hundredths of a degree.

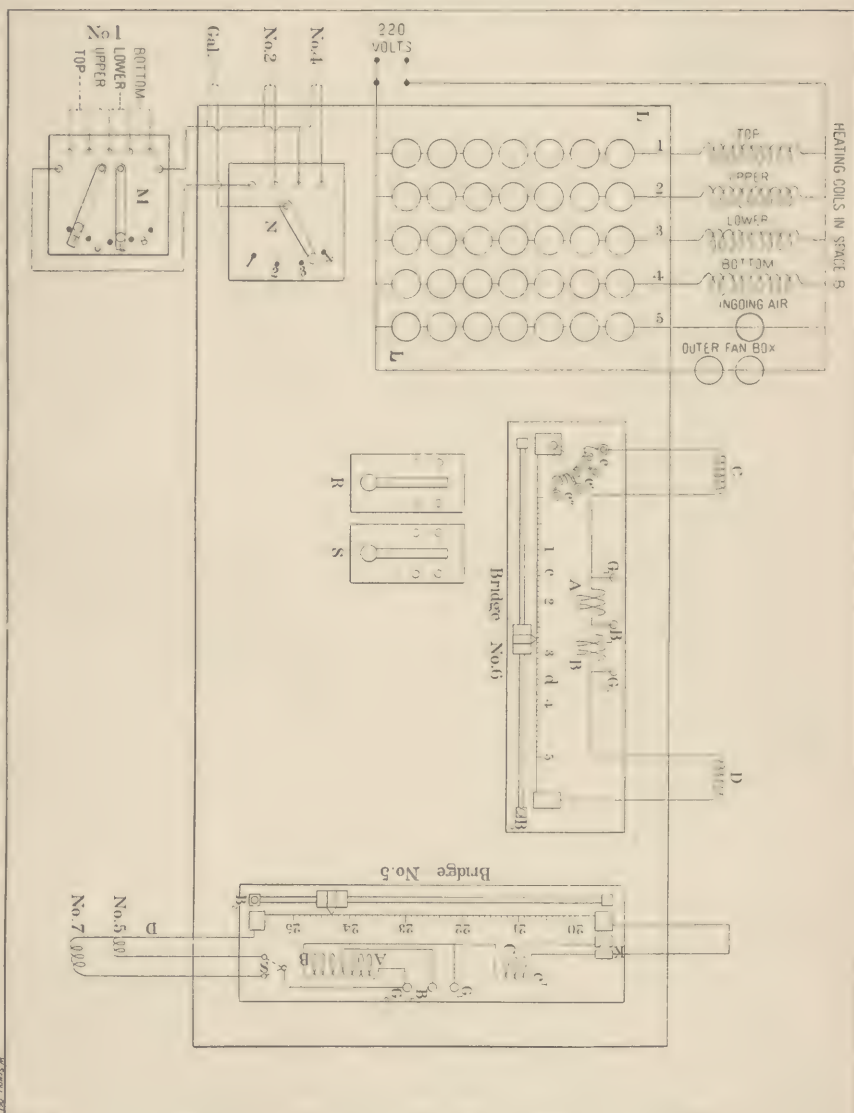
The rate at which heat is taken up by the absorbers depends upon their temperature as compared with that of the surrounding space and the freedom of circulation of air around them. Three methods are employed to diminish this rate below the maximum. First, the water may be allowed to enter at a higher temperature than the minimum of 2° C.; second, the water may be made to flow slowly through the absorbers so that its average temperature is higher; and third, shields may be put around the absorbers. Deep copper troughs J, J, hang under the absorbers (see fig. 2), one on each side and one on each end. The side troughs or shields can be operated from without by means of cords passing over pulleys L, L, which are wound up by rods reaching through the side of the calorimeter. Raising a shield around a portion of the absorber impedes the circulation of the air, the colder air within the shield being able to escape only by rising and flowing over the sides. As these shields can be raised to any desired point, and the temperature and rate of flow of the entering water can be regulated at will, any desired rate of absorption from 1 to 250 calories per hour, its maximum rate, can be obtained.

DETERMINING THE TEMPERATURE OF THE CALORIMETER.

In order to measure, not only the total amount of heat evolved by the subject, but also the rate at any and all times, it is necessary to keep the interior temperature of the calorimeter very nearly constant, and also to measure the small changes in temperature which may occur. For this purpose we have mounted six coils of No. 32 copper wire near the walls of the chamber, connected them in series with one another, and joined them to a slide-wire bridge (No. 5, Pl. VI) outside, so graduated as to read off the temperatures directly in degrees Centigrade, 1° extending over a hundred millimeters on the scale. Thus

DIAGRAM OF ELECTRIC APPARATUS AT THE OBSERVER'S TABLE.

Bridge No. 5 is a special Wheatstone bridge used in measuring the temperature of the respiration chamber. Bridge No. 6 is used to measure the difference of temperature of the ingoing and outgoing water. R, S are two electric keys. L, L is a bank of incandescent electric lamps used as variable resistance. M, N are two multiple switches.



the temperature is read to the hundredth of a degree. This bridge is similar to No. 6. A and B are the proportional arms of the bridge, here equal to each other, C is the comparison coil mounted on the bridge. The wire of coil C (as well as both bridge wires) was kindly furnished by the Weston Electric Instrument Company, and has a zero temperature coefficient, so that its resistance is constant. Hence the position of the slider is changed only when the temperature of the copper thermometers D varies. At K is a switch for short circuiting the small coil *c'*. When this is closed the scale reads from 17° C. to 22° C.; when open, from 20° C. to 25° C. The copper coil D, which forms the fourth arm of the Wheatstone bridge, is subdivided into six separate coils. Two of these are mounted on each side of the chamber and one on each end, each being at a different height M. M, M (fig. 2). Thus they indicate a fair average temperature. These coils are wound on light wooden frames (fig. 7), and are covered by a perforated brass tube. They are thoroughly insulated from the copper wall, and further protected from injury by guards O (fig. 2). They are very sensitive to slight changes in the temperature of the air.

A second set of similar coils is inclosed in copper boxes and attached in close thermal contact to the copper walls. They may be joined to the same bridge by a key, S, and indicate the temperature of the copper walls. These copper coils, with their slide-wire bridge, we call the "copper thermometers." A mercury thermometer passes through the wooden and zinc walls, and its bulb lies in a copper pocket which is soldered to the copper wall. This gives the temperature of the copper at that place, and its readings are compared with the "copper thermometer" readings.

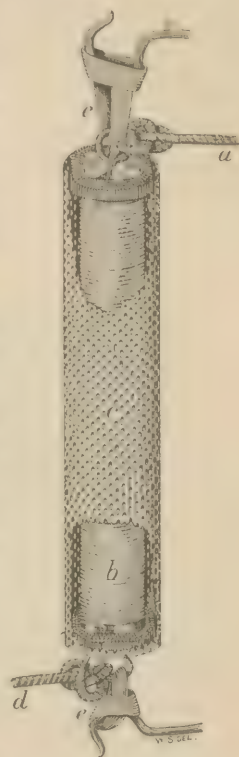


FIG. 7.—Coil of copper thermometer. These coils are mounted on the inner wall of the respiration chamber. They are joined in series, and indicate by their varying resistance the fluctuations in temperature of the calorimeter.

THE VENTILATING AIR CURRENT.

MEASURING AND REGULATING THE TEMPERATURE OF THE INGOING AIR.

The temperature of the outgoing air will be the same as that inside the chamber. If the ingoing air can be kept at the same temperature there will be no gain or loss of heat due to the circulation of the air.

The ingoing air passes through the "regulator" before entering the

chamber. This regulator, shown in fig. 8, is a copper cylinder 76 centimeters (30 inches) long and 18 centimeters (7 inches) in diameter. Within this is another cylinder 5 centimeters (2 inches) in diameter extending through the ends of the outer one. On the outside of this small cylinder are soldered eight vanes *V*, which reach nearly to the outside wall, thus increasing the effective area of the cylinder, which is filled with water to increase its capacity for heat. The air comes to the regulator a few degrees too cold, and is warmed by an incandescent lamp *L*, placed in the pipe. The current in the lamp is varied to give the re-

quired amount of heat.

After passing over the lamp and being warmed to about the desired temperature the air enters the regulator *S*, where it attains its final uniform temperature. If it enters a little warmer it will impart its surplus heat to the water in the smaller cylinder *T*, while if it enters slightly cooler it will receive heat from the same source. Thus it will enter the chamber through the tube *U* at a nearly constant temperature. This regulator of large capacity for heat steadies the temperature of the air current as the massive fly wheel of an engine steadies its speed.

Within the chamber is the "vestibule" (fig.

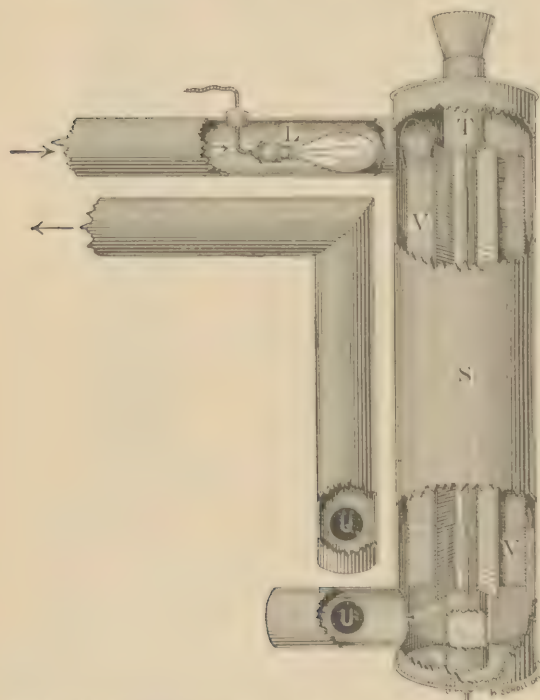


FIG. 8.—Air temperature regulator. The ventilating current of air passes through this regulator on its way to the calorimeter and the temperature is raised by the lamp *L*, or lowered by water circulating in the cylinder *T*, as may be necessary to make it the same as the temperature of the air escaping through the exit pipe *U*.

9), through which pass the currents of ingoing and outcoming air. This is a double-walled copper chamber, divided into two portions by a double-walled partition. The outcoming air enters the top and passes out through the tube *U*₂. This space will then have the temperature of the outcoming air. In the same way the ingoing air enters through the tube *U*₁ and leaves at the bottom. The lower space is then at the temperature of the ingoing air. Extending through the partition on either side are twenty-four pairs of iron German-silver thermo electric couples. These are connected to the galvanometer through point 4 of switch *N*

(Pl. VI), and if there is any difference of temperature between the air in the two spaces it will cause a deflection of the galvanometer. If this shows that the ingoing air is cooler than the outgoing, the current in the lamp (fig. 8) is increased. If the air should require to be cooled, as rarely occurs, this may be effected by drawing off a portion of the water and replacing it by colder water.

REFRIGERATING APPARATUS.

The refrigerating tank is shown in fig. 10. Liquid ammonia is supplied to the tank through the iron pipe marked P_3 from an ammonia machine in another part of the room. This liquid ammonia, initially at high pressure, passes through a reducing valve and flows into the coil of iron pipe shown in the figure. Here it evaporates, as it flows around the coil, as rapidly as heat can be absorbed from the solution of calcium chlorid which fills the tank. The temperature of this solution is thus reduced to about -18° or -20° C. The coil of pipe through which the ammonia passes consists of 88 meters (287 feet) of 2.5 centimeters (1 inch) extra-heavy pipe electrically welded so as to form one continuous tube. There are two sets of air refrigerators or "freezers" in the tank. The first is marked A, and is made of sheet copper. It consists practically of two large U tubes of copper immersed in the brine and so connected by horizontal elbows that the whole forms a compact mass a meter in height and a little over 20 centimeters square. Copper vanes radiating from the outside of the pipes increase the cooling surface. The air enters the pipe P_1 from out-of doors laden with more or less moisture. Reaching the freezer A its temperature is quickly lowered nearly to that of the surrounding brine and nearly all of its moisture is deposited upon the inner walls of the freezer. Before the condensation of moisture is such as to threaten to close the air space the freezer is removed and another put in its place. The air leaving the freezer A passes along the pipe P_2 to the calorimeter, being warmed to the temperature of the room before reaching the chamber. Its moisture content as it enters the calorimeter is quite uniform.

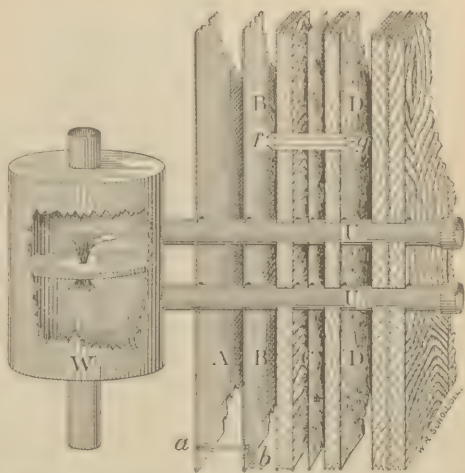


FIG. 9.—"Vestibule." The object of this apparatus is to facilitate the comparison of the temperature of the incoming and outgoing ventilating currents of air. The air enters the lower part of the vestibule through the lower pipe U_1 and leaves the upper part through U_2 . The thermo-electric junctions set in the partition between the upper and lower parts of the vestibule indicate any difference of temperature between the entering air and that which is about to flow out.

Returning from the calorimeter laden with water vapor, the air passes through the second system of refrigerators or freezers, in which the greater portion of this moisture is condensed. But in order to be able to collect and measure the deposited moisture for any given period, this system of freezers is differently constructed from that used for the

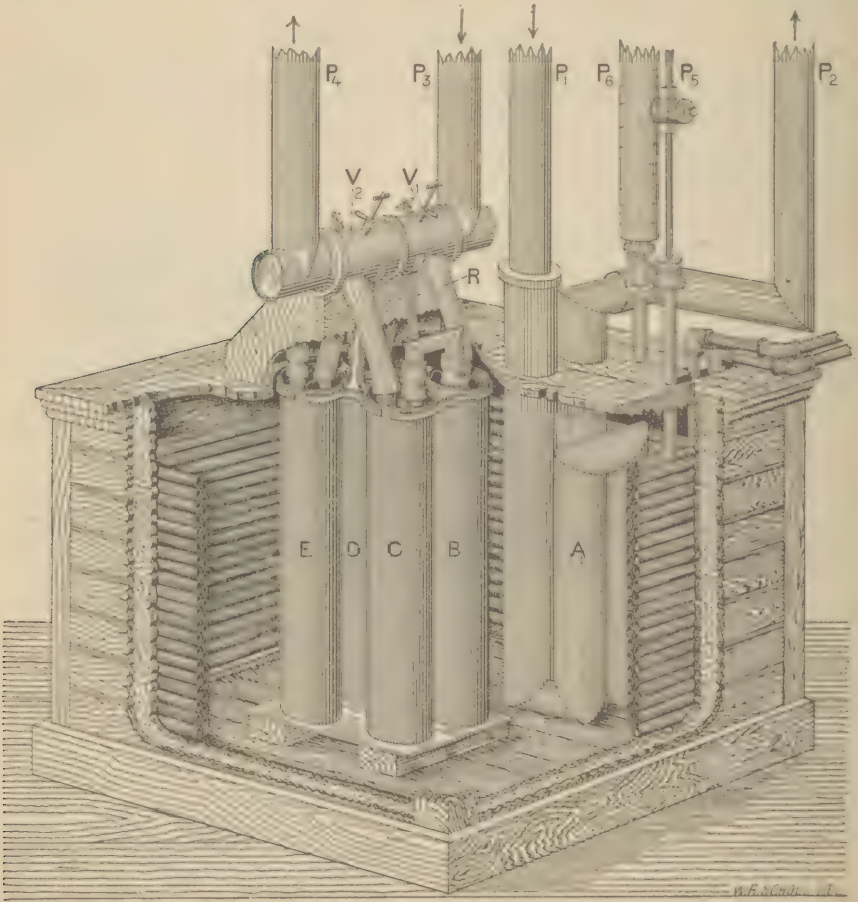


FIG 10. Refrigerating apparatus. The chief object of this is to remove the greater portion of the moisture from the ventilating current of air before it enters and after it leaves the respiration chamber. For this purpose the air is passed through copper cylinders or "coolers," A, E, immersed in brine (of calcium chloride) which is cooled to a temperature of -18° to -20° C by aid of ammonia expanding in the coiled pipe seen against the sides of the tank in the figure. The air flows through the cooler A on its way to the respiration chamber, and through B and C or D and E on its way from the chamber to the pumps. The valves V_1 and V_2 are used to direct the outgoing air current from one pair of cylinders to the other.

incoming air. Four cylindrical brass vessels are clamped together, as shown in the figure, and fitting closely inside them are four cylinders or freezers made of sheet copper. One of these freezers is shown in fig. 11. It is about 57 centimeters (22.5 inches) long and 12 centimeters (4.75 inches) in diameter, and is divided vertically by a partition, not shown

in the figure, which extends from the top nearly to the bottom. The air enters through a tube in the top, flows down to the bottom, and, rising on the other side of the partition, passes by means of a double-elbow connection to a second freezer, where the larger portion of the water not removed by the first freezer is condensed. In order to give more cooling surface, vanes of sheet copper are soldered to the interior surface of the cylinders extending to within a short distance of the middle partition. The space between the inner cylinder or freezer and the outer protecting jacket is filled with 90 per cent alcohol, in order to insure free passage of heat from the air current to the cooling brine. The freezers are removed and weighed at intervals, generally of six hours. In order that this can be done conveniently and without interfering with the regular flow of the air current two pairs of cylinders are used and a device is employed by which the current can be easily diverted from one pair to the other. This latter device we have called a "valve box." It consists, essentially, of two pieces of brass pipe, 10 centimeters (4 inches) in diameter, placed end to end. The adjoining ends are separated by a disk of so-called fibroid, which serves to prevent the passage of both air and heat from one tube to the other, while the open ends are connected to the air pipes P_3 and P_4 (fig. 10, p. 30). The valve boxes are also provided with apertures and brass tubes to connect them with the freezers. An arrangement is made for conveniently opening and closing these apertures by rubber stoppers, which are held by brass rods reaching through the walls of the valve box and worked from the outside. Two openings on one side are connected with one pair of freezers, while the two on the other side are closed. When it is desired to change the freezers the current is diverted from one pair to the other by means of these stoppers. The first pair of freezers is then taken out, warmed, dried, and weighed, the increase in weight representing the moisture condensed from the air current during the period.

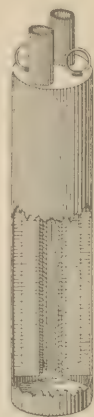


FIG. 11.—Condensing cylinder of refrigerating apparatus. One of these cylinders fits closely inside each of the fixed cylinders B, C, D, E, shown in fig. 10. The larger part of the moisture of the outgoing air current is deposited in these inside cylinders.

METER PUMP FOR REGULATING, MEASURING, AND SAMPLING THE VENTILATING AIR CURRENT.

Two forms of apparatus have been used for maintaining the air current and measuring its volume. The first consisted of an exhausting air pump used in connection with a special form of gas meter made by Elster in Berlin. With this we were unable to make measurements as accurately as seemed desirable to us.

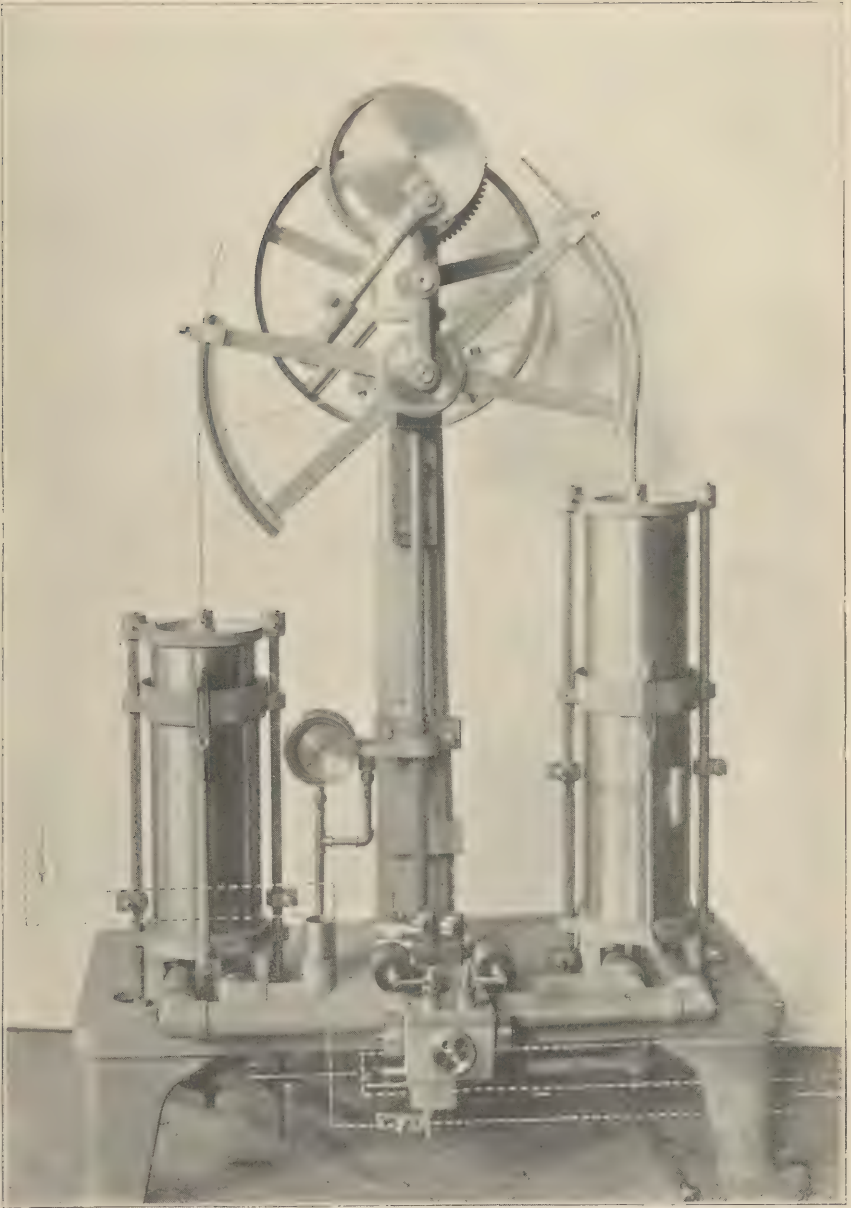
For taking samples of air for analysis aspirators (Pl. VIII, p. 34), containing 150 liters, were employed at the outset and are still used. The measurements with these have been found quite accurate. The most

satisfactory arrangement which we have found, however, and one which serves the threefold purpose of maintaining the air current, measuring its volume, and delivering aliquot samples of convenient volumes for analyses is an apparatus designed and made by Mr. O. S. Blakeslee and appropriately designated by him as a "meter pump." This is shown in Pl. VII. The essential parts for maintaining the air current and measuring its volume are cylinders of steel. There are two pumps, which work synchronously. Three steel cylinders are employed for each pump. The inner and outer cylinders are arranged concentrically, with a narrow annular space between them. This space is nearly filled with mercury. Between the inner and outer cylinders, which are stationary, plays a third cylinder, its lower portion being immersed in the mercury. This moving cylinder is closed at the top and is raised and lowered by a walking beam. The length of the stroke of the cylinder is determined by suitable stops, and the volume of air delivered at each stroke is constant. The temperature of the pump is kept practically constant, so that the mass of air of each stroke is constant. Like the moving cylinder, the inner cylinder is also covered at the top, but through this cover are two circular apertures, opened and closed alternately by an automatic valve.

The pump is driven by a belt on the large pulley, shown back of the walking beam, from a countershaft overhead. The speed is reduced by gearing, so that the face wheel in front rotates about ten times a minute. On the same shaft with the walking beam is a sleeve with a projecting arm, which is nearly hidden behind a portion of the walking beam. The end of this arm is attached to the face wheel by a connecting rod, as shown in the figure. This conveys an oscillatory motion to the sleeve, which is transmitted to the walking beam by the straight steel springs, the ends of which are connected at about the middle of the arcs.

The moving cylinders are suspended from the circular ends of the walking beam by flexible steel straps, each of which is wrapped around the end of the beam as the cylinder rises, as shown at the right in the figure. The length of the stroke is determined by stops on the rods at the sides of the pumps. These rods are fastened at the upper ends to the moving cylinders. The cylinders are thus stopped before the connecting rod has reached the end of its stroke or "dead point," and therefore the sleeve continues to turn after the walking beam and cylinders have come to rest. This is made possible by the long steel springs which drive the walking beam, as they bend enough to allow the sleeve to turn a little after the walking beam has been stopped.

During this short interval, while the cylinders are at rest, the valves are reversed by means of compressed air, so that as either cylinder descends the air will flow into the exit pipe. As seen in the figure, there are two pipes running under each pump. These pipes extend up inside the pump to the top of the stationary cylinders, the ends just reaching through the bottom of the pump proper. The valve is so arranged



BLAKESLEE METER PUMP.

The dotted lines show the positions of the pipes through which the main air current enters and the samples for analysis pass out.

that when one of these pipes is closed the other is open. In front of the standard carrying the driving mechanism of the pump is seen a small rod which extends below the base. This is driven from the sleeve by a pair of beveled gears, and hence it also has an oscillating movement. At the lower end it carries an arc, at each end of which a pin projects radially. A portion of this arc and the two pins may be seen near the bottom of the figure. One pin set in the slit near the end of the arc is crossed by the lower of the four dotted lines at the seventh dot from the left-hand end. The pin at the other end shows as a white dash a little to the right and near the second dotted line. Just at the right of the first pin is seen a vertical pin. In the position shown the pump is not quite at the end of its stroke. When the cylinders are brought to rest the moving pin will be very near this vertical one, and an instant later it will carry it to the right. This opens a port in the compressed-air chamber; the air escapes into a cylinder similar to one on a steam engine; the piston makes one stroke, which reverses the valves in both pumps, setting one so that air may be drawn in from the in-going pipe and the other so that the air may be expelled into the exit pipe. All this is done while the cylinders are at rest, and thus the air within them is at atmospheric pressure. The volume of each cylinder is known from its dimensions, and an automatic counter records the number of strokes.

In front of the base of the standard are seen the electro-magnets used in taking the samples for analysis. Below them is the chamber through which all of the air from the exit pipe must pass before it can escape. There are three openings from this chamber—one in front and one at either side. From the side openings are pipes (shown by the dotted lines) leading to the receptacles for holding the samples before analysis, termed briefly "pans." Likewise a pipe placed on the opening in front conducts the main current of air to the boxes surrounding the pans. This gives the same atmosphere both within and without the pans, and has been found by experiment to prevent a transfer of moisture through the sheet-rubber tops of the pans.

An ingenious method for taking these samples was devised by Mr. Blakeslee. Between the electro magnets and the standard is a ratchet wheel having 100 teeth. At each stroke of the pump this wheel is advanced by one tooth. Mounted on this wheel is a pin which closes an electric circuit once every revolution—that is, once in every hundred strokes. The current flows through one of the electro-magnets, drawing in its plunger. This motion closes the aperture in front, at the same time opening the one at the side, and thus allowing the air from a complete double stroke (both cylinders full) to pass into the corresponding pan. The electric circuit is then broken, which releases the plunger of the magnet, and the air continues to flow through the opening in front. A second pin in the toothed wheel, on the opposite side from the first, closes a second circuit through the other electro-magnet,

so that the intermediate fiftieth strokes are delivered into the other pan for duplicate analysis.

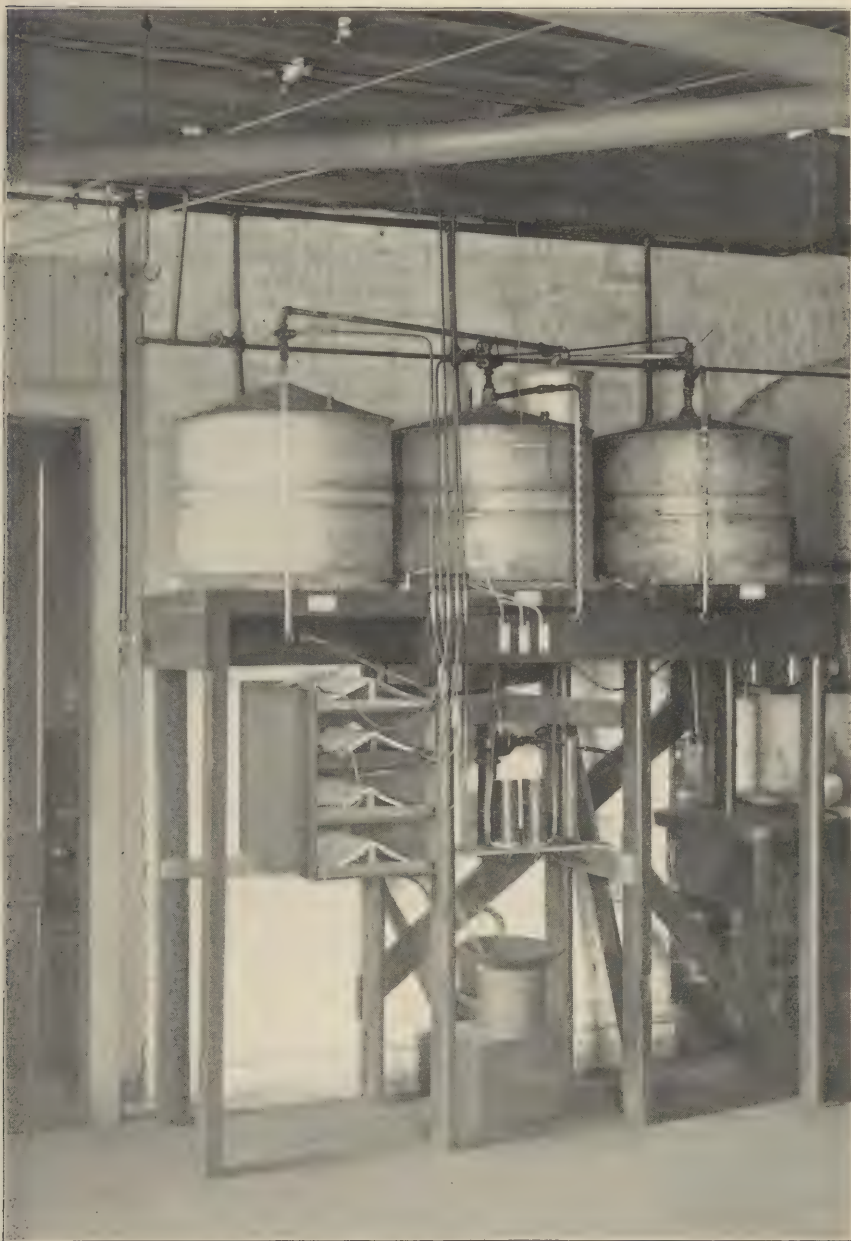
THE ASPIRATORS.

The form and use of the aspirators (Pl. VIII) were described at considerable length in a former publication¹ and need be but briefly described in this connection.

The aspirators are large cylinders made of galvanized sheet iron and having a volume of about 150 liters. The ends are conical, terminating both at the top and bottom in a small pipe. These aspirators are connected to the city water pipes, and by the opening of a valve each can be filled with water. When full the valve is tightly closed and the aspirator is ready for use. The water is drawn from the bottom of the aspirator by a rubber tube with a nozzle at its lower end. The flow is regulated by means of a pinchcock on the rubber tube and by raising or lowering the nozzle in order to diminish or increase the head of water. As the water level falls in the aspirator the nozzle must be lowered or the pinchcock loosened. The rate at which the water flows is taken every half hour, and amounts to not far from 425 cubic centimeters per minute, dependent upon the exact size of the aspirator and the period in which it is to empty. An automatic device for maintaining a constant flow of water has been made and is now being used with decided success. As the water runs out air must enter the top to take its place. This air is drawn from one of the pipes, from which a sample is desired, through the absorption tubes before entering the aspirator. The amount of water in the aspirator at any time is shown by a glass gauge along the side. The volume of the aspirator is taken between a mark on this gauge at the top, where the cross section is very small, and a similar mark at the bottom. This volume has been measured many times and is known very exactly.

The volume of the sample is obtained from the volume of the aspirator by adding several corrections. The temperature of the air in the aspirator is measured, and if it is different from that of the main current at the point where its volume is measured—i. e., the pump—the necessary correction is made. It is assumed that the air is saturated with water vapor, and as it entered perfectly dry a correction due to the pressure of the water vapor must be applied to find the volume of the air as it enters the aspirator. To this volume must be added the volume of the carbon dioxide and the water caught by the absorption tubes. This gives the volume of the sample taken from the main current, and this must be added to the volume measured by the pump to give the total ventilation. There are six aspirators, two being used for the analysis of the ingoing air and two others for the duplicate analysis of the outcoming air. In the meanwhile the third pair is being filled, so as to be ready for use when the others are empty.

¹ U. S. Dept. Agr., Office of Experiment Stations Bul. 44.



THE ASPIRATORS.

The aspirators are made of galvanized sheet iron and have a capacity of about 150 liters each. The absorbing tubes for determining carbon dioxide and water in the air drawn out of the respiration chamber rest upon roof-shaped supports on the small shelves below the aspirators at the left.

ARRANGEMENTS FOR SAMPLING AND ANALYZING THE VENTILATING AIR CURRENT.

After the incoming air has left the freezer samples for analysis are conveyed through a copper tube, 0.5 centimeter internal diameter, to the apparatus for determining the carbon dioxide and water. These samples are drawn by two aspirators (see p. 34), each of about 150 liters capacity. The outgoing air is sampled either by means of similar aspirators, or by means of the meter pump as already explained on page 34, or by both these methods. In the series of experiments carried on during the years 1896-1898 the method of sampling the outgoing air current by means of the meter pump, and the subsequent analysis of this sample, had not been perfected, and the results obtained by the aspirators were used entirely in the calculations of the amount of carbon dioxide in the outgoing air and of the water vapor not removed by the freezers.

The method of calculating the total carbon dioxide and water from the data obtained by use of the aspirators is as follows:

Let v = volume of aspirator in liters.

v' = corrected volume of aspirator in liters.

B = observed barometer.

b = observed barometer corrected for tension of aqueous vapor in aspirator.

T = temperature of pump.

t = temperature of aspirator.

w = total weight, in milligrams, of carbon dioxide or water removed from air in aspirator.

v_w = equivalent volume of water vapor in liters (weight in grams of water absorbed multiplied by 1.33).

v_c = equivalent volume of carbon dioxide in liters (weight in grams of carbon dioxide absorbed multiplied by 0.566).

m_1 = milligrams of carbon dioxide or water per liter.

V_p = volume, in liters, of air passed through pump.

V = total ventilation in liters = $V + v'$ (where analysis is in duplicate, v' here represents the sum of the volumes of the aspirators used).

W = total weight of carbon dioxide or water in ventilating air current.

$$\text{Then: } v' = v \cdot \frac{b}{B} \cdot [1 + \alpha(T - t)] + v_w + v_c.$$

$$m_1 = \frac{w}{v'}.$$

$$V = V_p + v'.$$

$$W = V m_1.$$

The method for collecting the sample delivered by the meter pump is as follows: The air from each fiftieth stroke of the pumps is col-

lected alternately in the "upper" and "lower" pans. These pans, which are made of heavy sheet tin, are 41 centimeters (16 inches) in diameter at the top, 28 centimeters (11 inches) at the bottom, and are 13 centimeters (5 inches) deep. A light, flexible rubber diaphragm made of the same dimensions exactly fits the interior of the pan, and its upper edge is securely fastened to the rim of the latter by means of a broad, stout rubber band. The air enters between the pan and the rubber diaphragm, and as the sample is delivered into the pan the diaphragm rises. The maximum capacity of the pan is such that it is possible for two samples to be delivered before any air is removed from it. At this point the rubber diaphragm stands inverted over the pan, and the whole presents the appearance of a double pan. In actual use the pans are not allowed to fill to the maximum, nor are they entirely emptied except at the close of the six-hour experimental periods.

The air is drawn from the pans by suction created by a small air pump. This pump partially exhausts the air in a large bottle, which serves as a regulator, so that the suction will be more constant. From this regulator rubber tubes lead to two Wolff bottles, one for each pan. These Wolff bottles are partly filled with water. Dipping below the surface of the water are two glass tubes, one of which opens directly into the air, while the other is connected with the tubes used for the absorption of the carbon dioxid and water vapor of the air coming from the pans. The tube opening directly into the air can be raised or lowered until the air is drawn from the pans at the desired rate—that is, sufficiently fast nearly to empty them before the delivery of the next sample. The air leaves the pans through a stopcock at the bottom and passes through the apparatus for the removal of the carbon dioxid and water.

If the pans were allowed to become entirely empty, and at the same time the suction were kept up, harm might result. To obviate this danger an automatic regulator was devised which completely shuts off the air passage from the Wolff bottles to the pans at a point immediately beyond the absorption tubes. Inasmuch as the pans were not used in the experiments of 1896–1898, with two exceptions (experiments Nos. 12 and 13), the self-regulating safety device is not described in this publication. To avoid danger of the air being withdrawn from the pan so slowly that a second sample may be delivered before the preceding one is removed, the rate of the current of air is so regulated by means of the Wolff bottles that the air will be withdrawn to the desired point and the automatic device will shut off the current several minutes before the time for the delivery of the next sample.

The method of analysis by use of the pans need not be further described in this publication.

The method of analysis of the air current consists in passing the sample through U tubes containing sulphuric acid for the removal of the water and soda-lime for the removal of the carbon dioxid. These

U tubes are about 12 centimeters (5 inches) in length and 1.5 centimeters ($\frac{3}{8}$ inch) in diameter. Those for the absorption of water are about two thirds filled with pumice stone drenched with concentrated sulphuric acid. In use these tubes are laid nearly flat, with just enough incline to the tube to avoid all danger of the acid coming in contact with the rubber stoppers through which the small connecting glass tubes pass. Detailed experiments have shown that the absorption of water vapor from an air current flowing at a rate as high as 750 cubic centimeters per minute is complete by the use of one such sulphuric-acid tube until the acid has taken up 1 gram of water, after which complete absorption from a current flowing at this rate can not be depended upon.

While only one U tube is necessary for the complete absorption of the water, a system of three U tubes is used for the complete removal of the carbon dioxid from the sample. Two of these are filled with soda-lime for the absorption of the carbon dioxid itself; the third contains sulphuric acid, which serves for the collection of the water taken up from the soda lime by the current of perfectly dry air passing over it. The soda-lime is made in the manner described in a former publication.¹ As the absorption of carbon dioxid takes place the yellowish color of the soda-lime gives place to the white color of the sodium and calcium carbonates that are formed, thus making it easy to see when a fresh tube is necessary. In the analysis of the incoming air, which contains very small quantities of carbon dioxid, one soda-lime tube, followed by a sulphuric-acid tube, is found sufficient, but for the outgoing air three tubes are used, as above described. When the soda-lime in one is nearly saturated the tube is removed, the second moved forward to take its place, and a fresh tube is added in place of the second. In this way the second tube in the system is always filled with fresh soda-lime. It has been found that two soda-lime tubes will remove all of the carbon dioxid from an air current flowing at a rate as high as 750 cubic centimeters per minute.

RESIDUAL CARBON DIOXID AND WATER VAPOR IN THE RESPIRATION CHAMBER.

The term "residual carbon dioxid and water vapor" is applied to the total amount of these materials remaining in the chamber at any given time.

In the check experiments described beyond, in which alcohol was burned, and in the experiments with man, the quantities of carbon dioxid and water vapor in the air of the chamber were found to be subject to considerable variations. In the experiments in which alcohol was burned in the chamber these fluctuations are due to the combustion of the alcohol at different rates; in experiments with a man they are due to differences in the amount of external or internal

¹ U. S. Dept. Agr., Office of Experiment Stations Bul. 44.

work done, and the consequent changes in the amount of material oxidized and the carbon dioxide and water eliminated.

In order to determine the exact amounts of carbon dioxide and water given off during any given time from the combustion of alcohol in a lamp or of food in the body, it is necessary to know not only the amount of these respiration products in the ventilating air current during this period, but the amount in the chamber at the beginning and at the end. For this purpose a sample consisting of 10 or 12 liters of air is drawn from the interior of the chamber by means of a rubber tube passing through an opening in the cover of the food aperture. The number of milligrams of carbon dioxide and water vapor per liter found in the sample, multiplied by the total amount of air in the chamber (approximately 4,800 liters), gives the total amounts of these products in the chamber at the time the sample was drawn. Such analyses are made at the beginning of an experiment and at the close of each experimental period.

An increase in the residual carbon dioxide and water vapor during any experimental period indicates that more of these products were given off in this time than during the previous period, and that some of the excess has remained in the chamber. Conversely, a decrease in the carbon dioxide and water vapor during any experimental period indicates a smaller production of these products and the consequent removal of some of the substances in the chamber at the beginning of the period. In other words, the analysis of the air in the chamber gives data for determining a positive or negative correction which must be applied to the amount of respiratory products found in the ventilating air current in order to obtain the quantities of these products actually given off during any given time.

TESTS OF THE ACCURACY OF THE APPARATUS AS A CALORIMETER.

Two series of test experiments were instituted to ascertain whether the calorimeter would accurately measure a given quantity of heat generated within the respiration chamber. In the first series an electric current of measured strength flowing through a known resistance generated in a given time a quantity of heat which could be readily calculated. As there was no circulation of air and no water vapor produced, the problem was simplified. In the second series alcohol was burned within the chamber, a current of air circulating through it supplying the necessary oxygen and carrying away the products of combustion. Here the complications arising from a ventilating current of air and the production of a large amount of moisture were introduced. Evidently, if the calorimeter will accurately measure a known quantity of heat generated in these two ways, it may be employed with confidence to measure the heat generated by a living subject within the chamber. In the latter case, however, we can not expect as high a degree of accuracy as in the former, for the rate of evolution of heat is more vari-

able and the movement of the person or animal about the respiration chamber introduces disturbances which will prevent the highest degree of accuracy in the measurements; and furthermore the errors due to physiological causes may be considerable.

ELECTRICAL TEST EXPERIMENTS.

The arrangement of the apparatus in the electrical tests is shown in fig. 12. The current from the 220-volt mains passes into the respiration chamber through a variable resistance, RS , a Weston ammeter, Am , and two copper voltameters, V_m , where it passes through PQ , a coil of German-silver wire No. 30, having a resistance of about 100 ohms. A Kelvin balance in series with a known resistance, R_r , in oil, and a

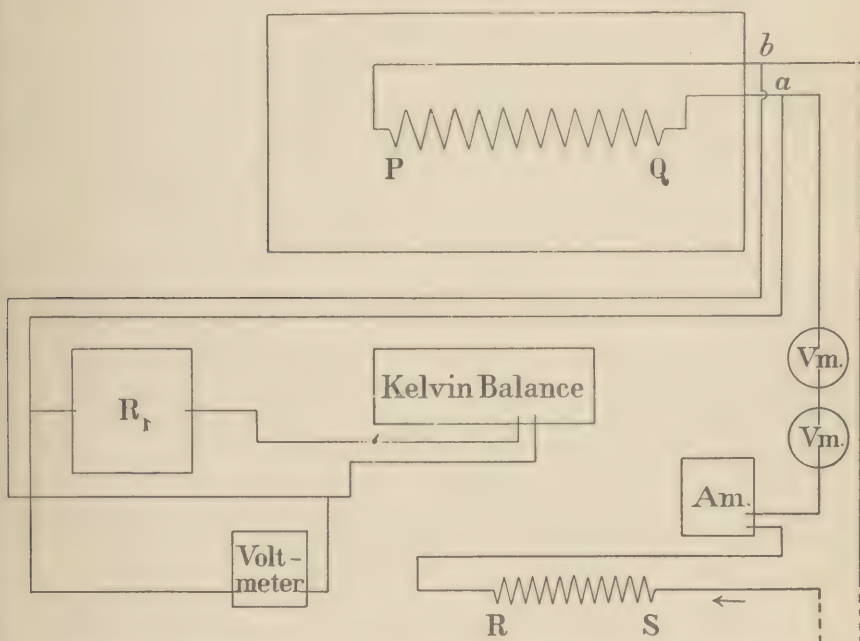


FIG. 12.—Arrangement of electric apparatus for generating heat in the test experiments.

Weston voltmeter in parallel with them are connected to the points a , b , and indicate the fall of potential through the resistance PQ . Usually an assistant keeps the current constant by adjusting the resistance RS . The current is given with considerable accuracy by the Weston ammeter, which in the first test experiment was used alone. But when the copper voltameters were employed the values for the current obtained with them were used.

The original data for the calorimetric measurements as observed by the operator at the observer's table are recorded by him in a notebook especially prepared for the purpose.

A sample page from the record of the test of March 20, 1897, is given

below. It gives the observations of one hour. The Weston instruments were used to measure the current and voltage, and the current was not maintained constant. Readings were recorded every two minutes, and the averages taken for the values of the current and the voltage.

TABLE 1.—*Sample page from record of calorimetric observations of experiment of March 20, 1897.*

Time P. M.	Inner wall.		Water circuit.			Inside temper- ature No. 5.	Electrical measure- ment.		Remarks.
	No. 1.	Parts.	T ₁ -T ₂ .	T ₂ -T ₁ .	Bridge No. 6.		Volts.	Amp.	
<i>h. m.</i>	-11		°C.	°C.	°C.	°C.			
3 00	0	$\begin{Bmatrix} 0 \\ +\frac{1}{2} \\ 0 \\ 0 \end{Bmatrix}$			9.62	19.95	71	0.61	
02	$\frac{1}{2}$				9.60	19.95	71	.61	
04	$\frac{1}{2}$				9.60	19.95	71	.61	
06	1		13.58		9.61	19.95	71	.61	
08	1		4.14	9.44	9.60	19.95	70	.61	
10	0				9.57	19.95	71	.61	
12	1				9.57	19.95	72	.61	
14	1 $\frac{1}{2}$		13.54		9.54	19.95	72	.61	5th 10 kilograms at 3.14.
16	1		4.14	9.40	9.52	19.95	71	.61	Average bridge reading, 9.56.
18	$\frac{1}{2}$	$\begin{Bmatrix} 0 \\ 0 \\ +\frac{1}{2} \\ 0 \end{Bmatrix}$			9.56	19.95	72	.61	9.56 - 0.13 = 9.43.
20	0				9.54	19.95	72	.61	9.43° × 10 = 94.30 calories.
22	$\frac{1}{2}$		13.57		9.54	19.95	70	.61	
24	1		4.15	9.42	9.51	19.94	69	.60	
26	1				9.56	19.94	70	.59	
28	1 $\frac{1}{2}$				9.57	19.93	69	.59	
30	2	$\begin{Bmatrix} +1 \\ \frac{1}{2} \\ 0 \end{Bmatrix}$	13.58		9.58	19.92	70	.60	
32	1 $\frac{1}{2}$	$\begin{Bmatrix} \frac{1}{2} \\ 0 \\ -1 \end{Bmatrix}$	4.14	9.44	9.51	19.92	69	.61	
34	$\frac{1}{2}$				9.53	19.92	71	.61	
36	0				9.51	19.92	71	.61	
38	0		13.57		9.53	19.92	71	.61	
40	$\frac{1}{2}$		4.14	9.43	9.50	19.92	71	.61	
42	1				9.54	19.93	71	.61	
44	$\frac{1}{2}$	$\begin{Bmatrix} 0 \\ +1\frac{1}{2} \\ -\frac{3}{2} \end{Bmatrix}$			9.58	19.93	71	.61	
46	0		13.57		9.55	19.94	71	.61	
48	$\frac{1}{2}$	$\begin{Bmatrix} -2\frac{1}{2} \end{Bmatrix}$	4.16	9.41	9.55	19.94	74	.63	
50	0				9.46	19.95	73	.63	
52	0				9.46	19.96	73	.63	
54	$\frac{1}{2}$		13.54		9.46	19.96	74	.63	
56	$\frac{1}{2}$		4.17	9.37	9.49	19.97	73	.62	
58	$\frac{1}{2}$				9.39	19.97	72	.62	

In the first column the time is recorded. In the second column are the deflections, in scale divisions, of the galvanometer when joined to thermo-electric circuit (No. 1) of the walls of the respiration chamber. Numbers at the left side of the column indicate deflections to the left and show that the inner chamber is a little cooler than air space B. (See Pls. IV and V.) At 3.10, the air in B having been cooled slightly, the deflection is zero. Then it becomes positive for a few minutes and the air in B requires slight warming. The deflections during the hour

are on the average less than one division and indicate an average difference of temperature of about 0.004°C . But this difference is part of the time positive and part of the time negative, so that the algebraic average is only one-fifth of one division to the right, indicating that the inner chamber was on the average for the hour 0.0014°C . warmer than the surrounding space. By carrying these differences along from page to page, the adjustments are made so that the differences cancel each other, and there is no correction to apply for flow of heat through the walls for the whole experiment.

One division deflection corresponds, as already stated (p. 18), to 0.007°C . difference of temperature, and with this difference of temperature 4 small calories per minute, or 0.24 of a large calorie per hour, flow through the walls of the chamber. This was determined in the following manner: A current of 0.17 amperes was passed through a resistance within the calorimeter for four hours. The fall of potential was 43 volts, giving 7.3 watts or about 104 small calories per minute. The temperature of the chamber rose a little at first, but was constant during the latter part of the experiment, showing that all of the heat was escaping through the walls. The deflection produced by the thermo-electric elements of circuit No. 1 was about 25 divisions, remaining substantially constant for sometime before the end of the experiment. This gives 4 small calories per minute per scale division as the amount of heat flowing through the walls of the calorimeter. This may be called the radiation constant.

For an average deflection of one-fifth of one division the rate at which heat would be escaping from the interior of the calorimeter would be 0.048 calorie per hour. The amount of heat generated and carried away from the calorimeter was, in this experiment, 74 calories per hour. Thus the amount of heat passing through the walls is only $0.048 \div 74 = 0.00065$ of the total, or one sixteenth of 1 per cent, and would not be an appreciable error if uncorrected. It is, however, subsequently recovered by keeping the deflection slightly negative, as already explained.

In the third column are recorded the deflections observed when parts of the thermo-electric circuits are separately joined to the galvanometer, the four numbers being for the top, upper, lower, and bottom sections, respectively. These deflections are all small and make more certain the balance indicated by zero deflection of the entire system in series.

In the fourth column are recorded the readings of the two mercury thermometers, G and H (fig. 3), and the fifth column shows their difference ($T_2 - T_1$), which is the gain in temperature of the water flowing through the absorbing pipes. The sixth column shows the readings of bridge No. 6 for the same difference of temperature.

The bridge does not give the exact difference of temperature of the two coils, which are immersed in the water, its readings being always too high. However, it correctly indicates the variations of temperature between

the thermometer readings, and thus interpolations between the observed thermometer readings can be made. In actual practice the average of the bridge readings is reduced by the average difference between thermometer and bridge. For example, 10 kilograms ran out during the period of seventy-four minutes from 2 to 3.14 p. m. The average of the bridge readings for the seventy-four minutes, during which the 10 kilograms of water were passing through the absorbers, was 9.56. The correction to be subtracted to reduce the bridge readings to degrees centigrade (see p. 40) is 0.13. This gives an average difference of 9.43° , and hence 94.30 calories of heat were brought away in these seventy-four minutes. In the same way the difference of temperature for each 10 kilograms is determined. A tabular statement of the heat measured during the entire experiment from 9.07 a. m. to 10.26 p. m. is given in the following table:

TABLE 2.—*Summary of heat measurements, March 20, 1897.*

Time.	(a) Duration of period.	Calorimetric measurements.				Electrical measurements.				Tempera- ture of the inside by the copper thermometer No. 5.
		(b) Water.	(c) Differ- ence in tempera- ture by bridge No. 6.	(d) Cor- rected difference in tempera- ture, c — 0.13.	(e) Amount of heat, b d.	E Volt- age on coil.	I Cur- rent through coil.	W Watts, E I	(k) Calories, $W \times a \times$ 2378.	
<i>h.</i> <i>m.</i> <i>s.</i>	<i>Secs.</i>	<i>Kilos.</i>	$^{\circ}$ C.	$^{\circ}$ C.	<i>Calis.</i>	<i>Volts.</i>	<i>Amp.</i>			$^{\circ}$ C.
9 07 00										20.10
9 51 15	2.655	7	9.57	9.44	66.08	148.3	0.625	92.69	58.52	19.78
10 12 30	1.275	3	9.07	8.94	26.82	146.4	.618	90.48	27.43	19.82
11 11 00	3.510	8	9.51	9.38	75.04	142.7	.604	86.19	71.94	19.76
11 28 00	1.020	2	9.76	9.63	19.26	141.5	.596	84.33	20.45	19.84
12 46 00	4.680	10	9.76	9.63	96.30	141.7	.602	85.30	94.93	19.93
2 00 00	4.440	10	9.58	9.45	94.50	145.2	.617	89.59	94.59	19.93
3 14 00	4.440	10	9.56	9.43	94.30	144.7	.617	89.27	94.25	19.95
4 28 15	4.455	10	9.46	9.33	93.30	143.1	.604	86.43	91.56	19.91
5 41 45	4.410	10	9.37	9.24	92.40	143.9	.612	88.07	92.36	19.92
6 56 00	4.455	10	9.41	9.28	92.80	143.9	.612	88.07	93.30	19.94
8 10 15	4.455	10	9.21	9.08	90.80	142.3	.606	86.23	91.35	20.01
9 24 15	4.440	10	8.98	8.85	88.50	139.5	.594	82.86	87.49	19.99
10 26 00	3.705	8	9.10	8.97	71.76	138.0	.583	80.45	70.88	19.95
					1,001.86	Heat generated by elec-				
Capacity correction for 0.15°					= -9.00	tric current.....				
Heat measured by calorimeter.....					= 992.86					

When the rate of flow of the water is changed during the time of filling one water meter (10 kilograms), the difference of temperature is averaged for each part separately. Thus, in the first period of this experiment, at 9:51:15 (see table above), when 7 kilograms had been collected the rate was decreased. Hence the difference of temperature for the 7 kilograms and for the 3 kilograms are separately determined, and the sum of the corresponding amounts of heat (66.08 and 26.82) is the total for the 10 kilograms.

Column 7, Table 1, shows the inside temperature as determined by bridge No. 5. The eighth column shows the readings of the voltmeter. There was a resistance of 20,000 ohms in series with the voltmeter, the resistance of which was 19,210; hence its readings should be multiplied by $39210 \div 19210 = 2.041$. The average of the voltmeter readings for the 10 kilograms from 2 p. m. to 3.14 p. m. was 70.9; multiplying this by 2.041 gives 144.7, which appears in the seventh line of the seventh column of Table 2, page 42. The average current for the same period was 0.617 ampere, and is entered in the eighth column, page 42. The ninth column gives the product of current and electromotive force, or watts; and the tenth column the number of calories of heat, found by multiplying watts by the time in seconds and the constant factor 0.2378.

If we denote by C the current in amperes, by E the electromotive force in volts, and by t the time in seconds, then

$$C \times 10^{-1} = \text{the current in absolute C. G. S. units.}$$

$$\text{and } E \times 10^9 = \text{the electromotive force in C. G. S. units.}$$

The rate of work or the electrical power is given by the product of the current and the electromotive force,

$$= CE \text{ in watts,}$$

$$= CE \times 10^7 \text{ in C. G. S. units or ergs per second.}$$

Hence in the time t ,

$$\text{energy in ergs} = CEt \times 10^7.$$

If a calorie be defined as the amount of heat required to raise 1 kilogram of water 1 degree at 15°C . it will be equivalent to a definite number of ergs, which must be determined by experiment. The value given by E. H. Griffiths,¹ as the result of his elaborate work on the determination of the relation between the electrical units and those of heat is,

$$J = 4.1982 \times 10^7 \text{ ergs, at } 15^\circ \text{C.}$$

The average temperature of the water in the absorbers in our experiments was in every case between 8° and 10°C . The specific heat of water² at 10°C . is 1.0019³ times its value at 15°C , and hence it requires 1.0019 times as much heat to raise 1 kilogram 1 degree at 10°C . as at 15°C ., so that

$$J = 4.2062 \times 10^7 \text{ ergs, at } 10^\circ \text{C.}$$

This value is practically the same as that given by Professor Rowland⁴ for the mechanical equivalent of heat at 8°C ., and so appears to be the most nearly correct for our use.

¹ Phil. Trans. Royal Society [London], A, 1893. Proc. Roy. Soc., vol. 55.

² Bartoli and Stracciati, Bol. Men. Accad. Gioenia, 18, 1891, Apr. 26. Preston's Theory of Heat, p. 265.

³ As estimated from the figures of the table on p. 56—i. e., $1.0029 \div 1.0010 = 1.0019$.

⁴ Proc. Amer. Acad. Sci., 15 (1879), p. 75.

A recent recalculation of Rowland's value of the mechanical equivalent of heat¹ gives 4.200×10^7 , at 8°C ., and it has been suggested that the difference between this value and Griffith's is accounted for by the uncertainty in the value of the ampere, but as we use the same ampere as Griffith did we should use his value of J .

The energy of the electric current expressed in ergs being

$$CEt \times 10^7,$$

when expressed in calories becomes

$$\frac{CEt \times 10^7}{4.2062 \times 10^7} = CEt \times 0.23775.$$

Referring to Table 2, page 42, it will be seen that the total amount of heat generated by the current is 989.05 calories. The amount measured is 1,001.86 calories, exceeding that produced by the electric current by 12.8 calories. During the experiment the temperature of the chamber fell from 20.10° to 19.95° . The capacity for heat of the apparatus is equivalent to that of 60 kilograms of water—that is, it requires 60 calories to raise the temperature 1° . This was determined in the following manner:

The calorimeter was held at a constant temperature (23.8°) for several hours. A current of 1.77 amperes, at 33 volts, was then passed through it for two hours. The temperature slowly rose and, keeping the deflection of the No. 1 thermo-electric circuit zero, no heat was allowed to pass through the walls. At the end of this time the current was stopped and the calorimeter came to a constant temperature at 25.4° . The rise in temperature was thus 1.6° . The amount of heat generated by the electric current was 98.2 calories, or 61.5 calories per degree. Other determinations gave similar results, and the round number 60 was taken as a sufficiently exact value of the thermal capacity of the apparatus.

In the above case, where the temperature fell 0.15° , there will be $0.15^\circ \times 60 = 9.0$ calories which are absorbed and measured in addition to the heat from the current. Applying this correction, we have for the measured amount of heat produced by the current, $1,001.86 - 9.0 = 992.86$ calories, which is 3.4 calories, or 0.34 per cent, greater than indicated by the electrical determination. As the temperature was falling more rapidly at the beginning than at the end, the actual temperature of the apparatus was somewhat higher than that of the air inside, and so the actual fall in temperature might be slightly greater than 0.15° .

That the temperature of the air does not truly represent that of the apparatus when the latter varies rapidly is clearly shown at the beginning of this experiment. From 9.07 a. m. to 9.51 a. m. the temperature of the air fell 0.32° , which would correspond to 20 calories; but the extra amount of heat for that period is only $66.1 - 58.4 = 7.7$ calories, which indicates that the temperature of the calorimeter as a whole fell only 0.13° .

¹ Phil. Mag., 44 (1897), p. 169.

Taking the latter part of the experiment, from 12.46 p. m. to 10.26 p. m., when the temperature was nearly constant, the heat from the current is 716.3, while that measured is 718.4. As the temperature was 0.02° higher at the end than at the beginning, 1.2 calories must be added to this, making it 719.6, which is 3.3 calories, or 0.46 per cent, too great. However, as only the Weston instruments were used to measure the electrical energy in this experiment, this is as good an agreement as could be expected.

In the next experiment, which was made on March 25, the current was kept constant, and the voltage measured by a Kelvin balance in series with a resistance. An assistant kept the balance at zero by varying the resistance RS, fig. 12, in series with the coil inside. The Weston instruments were also in the circuit. The current was determined by a copper voltameter.

A sample page of the records of this experiment is shown in Table 3:

TABLE 3.—*Sample page from record of calorimetric observations of experiment of March 25, 1897.*

Time p. m.	Inner wall.		Water circuit.		Bridge No. 6.	Inside tempera- ture No. 5.	Remarks.
	No. 1.	Parts.	$T_1 - T_2$.	$T_2 - T_1$.			
<i>h. m.</i>			$^{\circ}C.$	$^{\circ}C.$	$^{\circ}C.$	$^{\circ}C.$	
		-21 $\frac{1}{2}$					
4 00	$\frac{1}{2}$	.....	.....	.....	9.65	21.33	
02	$\frac{1}{2}$	.....	.....	.....	9.64	21.33	
04	1	.....	.....	.....	9.60	21.33	
06	0	.....	.....	.....	9.60	21.32	5 kilograms at 4:06:45 at 9.68.
08	1	.....	.....	.....	9.57	21.32	Average bridge reading, 9.68.
10	1	.....	.....	.....	9.57	21.32	9.68 - 0.16 = 9.52 $^{\circ}$.
12	$\frac{1}{2}$	.....	.....	.....	9.55	21.32	9.52 $^{\circ}$ $\times$ 5 = 47.6 calories.
14	0	.....	13.12	.....	9.50	21.32	
16	0	.....	3.76	9.36	9.47	21.32	
18	$\frac{1}{2}$	.....	.....	.....	9.44	21.31	
20	1	.....	.....	.....	9.38	21.31	
22	1 $\frac{1}{2}$	$\left\{ \begin{array}{c} -1 \\ 0 \\ +1\frac{1}{2} \\ -3 \end{array} \right\}$	.....	.....	9.42	21.31	
24	0	.....	.....	.....	9.44	21.31	
26	$\frac{1}{2}$	.....	.....	.....	9.64	21.31	
28	$\frac{1}{2}$	.....	.....	.....	9.49	21.30	
30	0	.....	13.22	.....	9.43	21.29	
32	0	.....	3.85	9.37	9.55	21.29	
34	$\frac{1}{2}$	.....	.....	.....	9.68	21.29	
36	$\frac{1}{2}$	.....	.....	.....	9.75	21.29	
38	$\frac{1}{2}$	.....	.....	.....	9.87	21.29	5 kilograms at 4:38:15 at 9.55.
40	$\frac{1}{2}$	.....	.....	.....	9.81	21.31	Average bridge reading, 9.55.
42	$\frac{1}{2}$	.....	.....	.....	9.88	21.31	9.55 - 0.16 = 9.39 $^{\circ}$.
44	$\frac{1}{2}$	.....	.....	.....	9.88	21.31	9.39 $^{\circ}$ $\times$ 5 = 46.95 calories.
46	0	.....	.....	.....	9.88	21.31	
48	0	.....	13.52	.....	9.82	21.31	
50	1	.....	3.75	9.77	9.88	21.31	
52	1	.....	.....	.....	9.86	21.31	
54	1	.....	.....	.....	9.95	21.32	
56	2	.....	.....	.....	10.01	21.32	
58	2	.....	.....	.....	10.02	21.32	
		32 $\frac{1}{2}$ - 7 $\frac{1}{2}$					

The amount of heat passing through the walls is very small, as shown by the deflections of the thermo-electric circuit No. 1. The heat was brought away and measured at very nearly the rate at which it was produced, as is evident from the constancy of the temperature as shown by No. 5. The increase in the bridge readings toward the end of the hour is due to the fact that the water was flowing more slowly.

The summarized results of this experiment were as follows:

TABLE 4.—Summary of heat measurements, March 25, 1897.

Time.			Calorimetric measurements.					Electrical measurements.				Temperature of the inside by the copper thermometer, No. 5.
			(a) Duration of period.	(b) Water.	(c) Difference in temperature by bridge No. 6.	(d) Corrected difference in temperature, $c - 0.16$.	(e) Amount of heat, $b \times d$.	E Voltage on coil.	I Current through coil.	W Watts, $E \times I$.	(k) Calories, $W \times a \times .2378$.	
<i>h.</i>	<i>m.</i>	<i>s.</i>	<i>Secs.</i>	<i>Kilos.</i>	$^{\circ}C.$	$^{\circ}C.$	<i>Cals.</i>		<i>Amp.</i>			$^{\circ}C.$
11	17	00										21.42
11	42	30	1,530	4	9.63	9.47	37.88	100.58	0.996	100.18	36.45	21.43
12	08	30	1,560	4 ¹	9.56	9.46	37.60	100.58	.996	100.18	37.16	21.44
12	22	00	810	2	9.63	9.47	18.94	100.58	.996	100.18	19.29	21.44
1	13	00	3,060	8 ¹ ₂	9.49	9.33	74.64	100.58	.996	100.18	72.90	21.38
1	26	00	780	2 ¹ ₂	9.47	9.31	18.62	100.58	.996	100.18	18.58	21.38
1	50	00	1,440	4	9.39	9.23	36.92	100.58	.996	100.18	34.31	21.40
2	16	00	1,560	4 ¹ ₃	9.46	9.30	37.20	100.58	.996	100.18	37.16	21.43
2	29	45	825	2	9.52	9.36	18.72	100.58	.996	100.18	19.64	21.41
3	02	15	1,950	5 ¹ ₄	9.53	9.37	46.85	100.58	.996	100.18	46.46	21.46
3	34	30	1,935	5 ¹ ₄	9.71	9.55	47.75	100.58	.996	100.18	46.10	21.33
4	06	45	1,935	5 ¹ ₅	9.68	9.52	47.60	100.58	.996	100.18	46.10	21.32
4	38	15	1,890	5 ¹ ₅	9.55	9.39	46.95	100.58	.996	100.18	45.03	21.29
5	22	15	2,640	6 ¹ ₆	10.09	9.93	59.58	100.58	.996	100.18	62.89	21.32
							529.25	Heat generated by electric current.....				522.07
Capacity correction for 0.10°							= -6.00					
Heat measured by calorimeter							= 523.25					

The electrical energy was much more carefully determined than before, and was maintained constant throughout the experiment. The heat as measured and corrected is practically identical with that calculated from the current.

Another experiment was made the next day, March 26, in which a larger amount of heat was generated and measured. This experiment began in the morning and extended till late in the evening. During the first part, however, there was some uncertainty in the measurement of the temperature; accordingly, only the last seven hours are given. A sample page of the record and a summary of results are given in Tables 5 and 6.

TABLE 5.—Sample page from record of calorimetric observations of experiment of March 26, 1897.

Time P. m.	Inner wall.		Water circuit.		Bridge No. 6.	Inside temper- ature No. 5.	Remarks.
	No. 1.	Parts.	T ₁ -T ₂ .	T ₂ -T ₁ .			
<i>h. m.</i>			°C.	°C.	°C.	°C.	
5 00	-3½	$\left\{ \begin{array}{c} +2 \\ +1 \\ 0 \\ -1\frac{1}{2} \end{array} \right\}$			12.80	22.61	
02	0				12.80	22.61	
04	0				12.79	22.61	1st 10 kilograms at 5.04.
06	0				12.80	22.62	Average bridge reading, 12.73.
08	1				12.87	22.62	12.73 - 0.27 = 12.46°.
10	0				12.85	22.62	12.46° × 10 = 124.6 calories.
12	1½		15.97		12.84	22.61	
14	1½		3.42	12.55	12.78	22.62	
16	1½				12.72	22.62	
18	1½				12.80½	22.62	
20	1	$\left\{ \begin{array}{c} +1 \\ +1\frac{1}{2} \end{array} \right\}$			12.81	22.62	
22	½	$\left\{ \begin{array}{c} +1\frac{1}{2} \\ -1 \\ 0 \end{array} \right\}$			12.84½	22.62	
24	0				12.83½	22.62	
26	0				12.86	22.62	
28	0		15.93		12.76	22.63	
30	½		3.44	12.49	12.77	22.63	
32	0				12.87½	22.63	
34	½				12.77	22.64	
36	1				12.80½	22.64	
38	0				12.81	22.64	
40	1				12.81	22.64	
42	½		15.94		12.81	22.64	
44	½	$\left\{ \begin{array}{c} 0 \\ -\frac{1}{2} \\ 0 \\ -\frac{1}{2} \end{array} \right\}$	3.43	12.51	12.77	22.64	
46	0				12.78	22.65	2d 10 kilograms at 5:47:45.
48	1				12.79	22.65	Average bridge reading, 12.81.
50	½				12.86	22.65	12.81 - 0.27 = 12.54°.
52	0				12.83	22.65	12.54° × 10 = 125.4 calories.
54	½				12.79	22.65	
56	0		16.04		12.81	22.64	
58	0		3.47	12.57	12.85	22.64	
	7+11½						

TABLE 6.—Summary of heat measurements, March 26, 1897.

Time.	(a) Duration of period.	Calorimetric measurements.				Electrical measurements.				Tempera- ture of the inside by the copper therm- ometer No. 5.
		(b) Water.	(c) Differ- ence in temper- ature by bridge No. 6.	(d) Cor- rected differ- ence in temper- ature, c=0.27.	(e) Amount of heat, b × d.	E Voltage on coil.	I Cur- rent through coil.	W Watts, E × I.	(k) Calories, W × a × .2378.	
<i>h. m. s.</i>	<i>Secs.</i>	<i>Kilos.</i>	<i>°C.</i>	<i>°C.</i>	<i>Cals.</i>		<i>Amps.</i>			<i>°C.</i>
4 20 20										22.63
5 04 00	2,620	10	12.73	12.46	124.60	147.8	1.363	201.5	125.54	22.61
5 47 45	2,625	10	12.81	12.54	125.40	147.8	1.363	201.5	125.78	22.65
6 31 45	2,640	10	12.92	12.65	126.50	147.8	1.363	201.5	126.50	22.67
7 15 27	2,622	10	12.77	12.50	125.00	146.0	1.350	197.1	122.89	22.57
7 59 10	2,623	10	12.80	12.53	125.30	147.8	1.363	201.5	125.68	22.59
8 42 40	2,610	10	12.79	12.52	125.20	147.8	1.363	201.5	125.06	22.60
9 26 15	2,615	10	12.78	12.51	125.10	147.8	1.363	201.5	125.30	22.60
10 09 50	2,615	10	12.68	12.41	124.10	147.8	1.363	201.5	125.30	22.64
10 53 30	2,620	10	12.82	12.55	125.50	147.8	1.363	201.5	125.54	22.62
11 37 10	2,620	10	12.81	12.54	125.40	147.8	1.363	201.5	125.54	22.61
Capacity correction for 0.02°					1,252.10	Heat generated by elec- tric current				=1,253.13
					-1.2					
Heat measured by calorimeter					=1,250.9					

The current was maintained constant, as in the preceding experiment, and the voltage measured by the Kelvin balance. About 7 p. m. the voltage on the mains was lower than usual for some minutes, and the variable portion of the resistance was insufficient to maintain the voltage on the coil. Consequently the balance was set at a lower point and the current kept constant at this smaller value until it could be restored to its former value. This makes the average voltage and current for the fourth period smaller than the others. The totals show that the amount measured was 2.2 calories, or 0.18 per cent, too small. This, however, assumes that the measurements of temperature at the beginning and the end are accurate and that the temperature of the whole apparatus is the same as that of the air. An error of a few hundredths of a degree might throw the difference in the opposite direction. Since this change is so slight, and as all the measurements of the temperature are presumably equally reliable, it would be more accurate if the average of all was used in obtaining the capacity correction. This can be done by taking different portions of the experiment and applying the capacity correction to each portion; the average of the errors from the different portions will give a more probable value of the error of the experiment. The last two experiments are thus discussed in Tables 7 and 8.

TABLE 7.—Discussion of experiment of March 25, 1897.

Periods.	(e) Heat as measured.	Temperature No. 5.			(i) Capacity correction, $h \times 60$.	(j) Corrected heat, $e + i$.	(k) Heat put in by the current.	Error in heat measurement, $j - k$.
		(f) At the beginning.	(g) At the end.	(h) Change, $g - f$.				
	<i>Cals.</i>	$^{\circ}C$.	$^{\circ}C$.	$^{\circ}C$.	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>
1-4.....	375.1	21.42	21.33	-0.09	-5.4	369.7	368.1	+1.6
2-5.....	375.3	21.44	21.29	-0.15	-9.0	366.3	366.3	0.0
3-6.....	341.6	21.38	21.32	-0.06	-3.6	338.0	337.7	+0.3
	0.6				Sum.....	1,074.0	1,072.1	+1.9
	$\frac{0.6}{357.7} = 0.17$ per cent.				Avg.....	358.0	357.4	+0.6

TABLE 8.—Discussion of experiment of March 26, 1897.

Periods.	(e) Heat as measured.	Temperature No. 5.			(i) Capacity correction, $h \times 60$.	(j) Corrected heat, $e + i$.	(k) Heat put in by the electric current.	Error in heat measurement, $j - k$.
		(f) At the beginning.	(g) At the end.	(h) Change, $g - f$.				
	<i>Cals.</i>	$^{\circ}C$.	$^{\circ}C$.	$^{\circ}C$.	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>
1-6.....	752.0	22.63	22.60	-0.03	-1.8	750.2	751.5	-1.3
2-7.....	752.5	22.61	22.60	-0.01	-0.6	751.9	751.1	+0.8
3-8.....	751.2	22.65	22.64	-0.01	-0.6	750.6	750.6	0.0
4-9.....	750.2	22.67	22.62	-0.05	-3.0	747.2	749.6	-2.4
5-10.....	750.6	22.57	22.61	+0.04	+2.4	753.0	752.2	+0.8
	0.4				Sum.....	3,752.9	3,755.0	-2.1
	$\frac{0.4}{750.6} = 0.053$ per cent.				Avg.....	750.6	751.0	-0.4

In the first column is indicated the number of periods corresponding to the section of the experiment taken for discussion. In the second, (e), is the heat measured during the same period—i. e., the sum of the values in column (e), Tables 4 and 6. The next three columns show the change in temperature of the apparatus, and the necessary correction is given in the sixth column. Applying these corrections to the values in the second column gives the corrected heat in (j). The values of the heat generated, (k), are obtained by adding those in column (k), Tables 4 and 6, pages 46 and 48. The last column gives the differences between the heat generated and that measured, and the average of these shows the error of the apparatus. In these experiments the error averages about 0.1 per cent, which is as close as the electrical energy could be measured.

Another test of a somewhat different nature was made April 30. A small incandescent electric lamp, rated at 4 candlepower, but burned low, taking 4.21 watts, or 1 small calorie per second, was placed within the chamber and the heat given off was measured. The heat

being so small it was necessary to have the water enter at a temperature nearly as high as the air inside, and to flow in a very slow stream. The results of six hours' run are given in Table 9.

TABLE 9.—*Experiment with 4-candlepower electric lamp—Summary of heat measurements, April 30, 1897.*

Time.	(a) Dura- tion of period.	Calorimetric measurements.				Electrical measurements.				Temper- ature of the in- side by the cop- per ther- mometer No. 5.	
		(b) Water.	(c) Difference in tem- perature by bridge No. 6.	(d) Corrected difference in tem- perature, $c=0.09^{\circ}$.	(e) Amount of heat, $b \times d$.	E Voltage on lamp.	I Current through lamp.	W Watts, $E \times I$.	(k) Calories, $W \div a$ $\times .2378$.		
<i>h. m. s.</i>	<i>Secs.</i>	<i>Kilos.</i>	$^{\circ}\text{C.}$	$^{\circ}\text{C.}$	<i>Cals.</i>		<i>Amp.</i>			$^{\circ}\text{C.}$	
9 56 00										19.72	
10 11 45	945	1	1.82	1.73	1.72	5.61	0.75	4.21	0.95	19.70	
10 40 35	1,730	2	1.35	1.26	2.52	5.61	.75	4.21	1.73	19.65	
10 54 55	860	1	1.28	1.19	1.19	5.61	.75	4.21	.86	19.63	
11 38 45	2,630	3	1.15	1.06	3.18	5.61	.75	4.21	2.63	19.62	
1 55 00	8,175	9	.97	.88	7.92	5.61	.75	4.21	8.17	19.63	
2 22 30	1,650	2	.41	.32	.64	5.61	.75	4.21	1.65	19.66	
3 08 00	2,730	2.6	.61	.52	1.35	5.61	.75	4.21	2.73	19.72	
3 54 00	2,760	3.3	.95	.86	2.84	5.61	.75	4.21	2.76	19.73	
Heat measured.....					=21.37	Heat generated					=21.48

It will be seen that the measurement is very close. There is apparently a small capacity correction, which, if applied, makes the error in the opposite direction. It is so small, however, that it is impossible to say with certainty how much the correction should be.

As this amount of heat is only about 1 per cent of the maximum which the apparatus will measure and about 3 per cent of the heat usually measured, it is evident that there can be no appreciable loss or gain of heat by radiation or otherwise. We therefore believe that this calorimeter, with proper manipulation, will measure heat as accurately as it is possible to measure it by any other form of calorimeter.

ALCOHOL TEST EXPERIMENTS.

The electrical tests above described demonstrate the accuracy of the apparatus as a calorimeter when the evolution of heat inside the chamber is reasonably uniform, and there is no current of air passing through and no vaporization of water within the chamber. In experiments with men, however, the development of heat is less uniform; furthermore, a current of air is passing through the chamber, water and carbon dioxide are produced, and water is vaporized within it. In these experiments the principal measurements made with the aid of the apparatus are the amounts of water and carbon dioxide produced by the man and the heat given off from his body. In experiments where the external muscular work has been considerable the latter has been transformed into electrical energy, measured, and transformed

into heat. This heat has been measured with that given off directly by the body. The crucial test of the accuracy of the determinations of carbon dioxid, water, and heat must be made in test experiments under circumstances closely similar to those of the actual experiments with men. When ethyl alcohol is burned in air carbon dioxid, water, and heat are produced. If known quantities of alcohol be burned inside the chamber while a current of air is passing through, the conditions will approach very closely those of an experiment with man. To make these experiments accurate, the amount of alcohol burned must be exactly known and the combustion must be complete.

Several series of experiments were made in which alcohol was burned inside the chamber. The rate of flow of the ventilating current, the method of analysis of the incoming and outgoing air, and the method of measurement of heat were the same as if a man were inside the chamber.

COMPOSITION OF ALCOHOL USED—SPECIFIC GRAVITY.

When ethyl alcohol is diluted with pure water and no other compounds are present, the quantity of alcohol can be determined with reasonable accuracy, even to the fifth or sixth decimal place, by use of the pyknometer devised and described by Dr. Edward R. Squibb,¹ who has given more attention to the subject than anyone else of our acquaintance. Dr. Squibb has very kindly supplied us with a pyknometer calibrated by himself. He has also furnished us with a quantity of alcohol as nearly pure as it can well be prepared, and also with samples diluted with 12 per cent of water. He informs us that, while absolute alcohol absorbs moisture from the air with great avidity, a solution containing this proportion of water is very slightly altered on short exposure to the air. Dr. Squibb also informs us that the high grades of commercial ethyl alcohol are so nearly free from other substances than ethyl hydroxid and water, and that the composition is so slightly changed by the evaporation which takes place with careful manipulation, that the determination of the specific gravity by use of his pyknometer gives the composition with as great accuracy as is attained by combustion with oxygen by the ordinary process of analysis.

We desire to express our appreciation of the most valuable assistance rendered us by Dr. Squibb.

In tests here made we have used pure ethyl alcohol furnished by Dr. Squibb in some cases, but for the larger part of our work, including the alcohol tests with the respiration calorimeter, a high grade of commercial alcohol was used instead of the so-called absolute alcohol, because it can be more easily stored, weighed, and measured without change of water content. The specific gravity of this alcohol was determined at the time of each experiment. The variations in the different samples were small, the proportion of alcohol being not far from 90.5 per

¹Jour. Amer. Chem. Soc., 19 (1897), p. 111; Ephemeris, 2 (1884-85) p. 541.

cent by weight. From the percentage of alcohol present the amount of carbon dioxide and water that would be formed by complete oxidation is readily calculated as follows: One gram of ethyl alcohol (C_2H_5O) will yield on oxidation 1.9110 grams of carbon dioxide and 1.1737 grams of water.¹ One gram of a mixture of alcohol and water containing 90.77 per cent absolute alcohol (the strength of that used in the first three tests) will give 1.9110×0.9077 , or 1.7346 grams of carbon dioxide, and 1.1737×0.9077 , or 1.0654 grams of water from the combustion of the ethyl alcohol in addition to the 0.0923 grams of water present in the mixture, making a total of 1.1577 grams of water from 1 gram of the alcohol mixture used. The estimates of the quantity of heat produced by the oxidation of a gram of each of the different specimens of alcohol are made by use of the factor 7.067 calories for the heat of the combustion of 1 gram pure ethyl alcohol as explained beyond. The strength of the alcohol used in each test, and the factors for the computation of the amounts of carbon dioxide, water, and heat given off per gram, are shown in Table 10.

TABLE 10.—*Strength of alcohol used in the different tests and the corresponding amounts of carbon dioxide, water, and heat yielded by the combustion of 1 gram.*

Test No.	Ethyl hydroxid by weight.	Products of oxidation of 1 gram.		
		Carbon dioxid.	Water.	Heat.
	<i>Per cent.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Sm. cals.</i>
1.....	90.77	1.7346	1.1577	6.415
2.....	90.77	1.7346	1.1577	6.415
3.....	90.77	1.7346	1.1577	6.415
4.....	90.61	1.7316	1.1574	6.403
5.....	90.63	1.7319	1.1574	6.405
6.....	90.26	1.7249	1.1567	6.379
7.....	90.26	1.7249	1.1567	6.379
8.....	90.61	1.7316	1.1574	6.403
9.....	90.26	1.7249	1.1567	6.379

HEAT OF COMBUSTION OF ALCOHOL—DETERMINATION WITH THE BOMB CALORIMETER.

The heat of combustion of the alcohol used in the tests was determined by the bomb calorimeter.² Two methods were used. In one the

¹Using the values O = 16, C = 12, H = 1.008 for atomic weights, as proposed by the committee on atomic weights, of the American Chemical Society, Jour. Amer. Chem. Soc., 20 (1898) p. 163. See also Richards, Amer. Chem. Jour., 20 (1898), p. 543; also the values proposed by the committee of the German Chemical Society, Ber. Deut. Chem. Gesell., 31 (1896), p. 2761.

²The form of apparatus used, which is a modification of that of Berthelot, is described in U. S. Dept. Agr., Office of Experiment Stations Bul. 21, and Connecticut Storrs Sta. Rpt. 1897. The determinations of the heats of combustion of alcohol used for these tests and in other experiments connected with the general investigation were made by Dr. O. F. Tower and the details of the work are not yet published.

alcohol was poured upon cellulose absorption blocks.¹ The weighing was made with due precautions to prevent, if possible, any loss by evaporation. The alcohol and absorption blocks were burned in the calorimeter, a correction being applied for the heat of combustion of the absorption block used. Eight determinations were made by this method with commercial alcohol of high grade and of different strengths.

The use of absorption blocks is objectionable because of the difficulty of avoiding evaporation of alcohol during the process of weighing and transferring to the bomb, and because of the considerable and not absolutely certain correction to be applied for the heat of combustion of the absorption blocks used. The first difficulty was avoided entirely and the other partially by the second method employed. In this the alcohol was inclosed in small gelatin capsules by which the evaporation is prevented. The weight of gelatin is also small and the correction for its heat of combustion is less than with the absorption blocks. Eight determinations were made with Squibb's alcohol and nine with commercial alcohol, such as was used in the tests in the respiration calorimeter. The results obtained by both methods are shown in Table 11.

TABLE 11.—*Determination of heats of combustion of alcohol in the bomb calorimeter.*

	Ethyl hydroxid by weight.	Heat of combustion per gram actu- ally de- termined.	Calcu- lated heat of com- bustion per gram of ethyl hydroxid.
Alcohol contained in absorption blocks:	<i>Per cent.</i>	<i>Small cals.</i>	<i>Small cals.</i>
Specimen No. 1.....	89.9	6,348	7,062
Do	89.9	6,345	7,058
Do	89.9	6,377	7,093
Average of above 3.....			7,071
Specimen No. 2.....	81.3	5,744	7,063
Do	81.3	5,763	7,090
Average of above 2.....			7,076
Specimen No. 3.....	72.5	5,132	7,078
Do	72.5	5,094	7,030
Do	72.5	5,132	7,078
Average of above 3.....			7,062
Average of above 8.....			7,069
Alcohol contained in gelatin capsules:			
Specimen No. 4.....	88.0	6,205	7,050
Do	88.0	6,224	7,072
Do	88.0	6,209	7,055
Do	88.0	6,199	7,044
Do	88.0	6,204	7,050
Do	88.0	6,203	7,049
Do	88.0	6,227	7,076
Do	88.0	6,240	7,090
Average of above 8.....			7,061

¹ As described by Kellner, Landw. Vers. Stat., 47 (1896), p. 297.

TABLE 11.—*Determination of heats of combustion of alcohol, etc.—Continued.*

	Ethyl hydroxid by weight.	Heat of combustion per gram actu- ally de- termined.	Calcu- lated heat of com- bustion per gram of ethyl hydroxid.
Alcohol contained in gelatin capsules—Continued			
Specimen No. 5.....	90.61	6,435	7,101
Do	90.61	6,384	7,046
Do	90.61	6,401	7,064
Do	90.61	6,383	7,045
Do	90.61	6,403	7,066
Do	90.61	6,397	7,060
Do	90.61	6,436	7,103
Do	90.61	6,433	7,099
Do	90.61	6,386	7,047
Average of above 9.....			7,070
Average of above 17.....			7,066
Average of above 25.....			7,067

The heat of combustion when determined by the first method ranged from 7,030 to 7,090, and averaged 7,069 small calories per gram of absolute alcohol.

The results obtained by the second method with Squibb's alcohol ranged from 7,044 to 7,090 small calories, and averaging 7,061 small calories per gram, absolute alcohol. The results of similar determinations with the commercial alcohol ranged from 7,045 to 7,103 small calories, and averaging 7,070 small calories per gram, absolute alcohol. The average of these 17 determinations with alcohol in gelatin capsules gives 7,066 small calories, practically the same result as was obtained by the use of the absorption blocks. Considering the range of variation in these different determinations, we would hardly be justified in assuming that the figure 7,067 represents exactly the heat of combustion of ethyl hydroxid. There is reason to hope, however, that some of the sources of error in the determinations may be partially eliminated, and that thus more reliable results may be obtained. It is worthy of note that Berthelot and Matignon¹ obtained the figure 7,068 as the average of two determinations, which gave 7,067.3 and 7,068.5 small calories, respectively, at 13°. The average 7,068 corresponds to 7,079 at 20°, a value very close to those obtained here.

The heat of combustion of alcohol of any given dilution with water is found by multiplying the heat of combustion of 1 gram of absolute alcohol by the percentage present in the specimen. Thus in the specimen of alcohol used in the first three tests the heat of combustion was $7,067 \times .9077$, or 6,415 small calories per gram.

While the heat of combustion of 1 gram of absolute alcohol is thus 7,067 small calories per gram, this does not represent the amount of

¹ Ann. Chim. et Phys., 6. ser., 27 (1892), p. 312.

heat that is given off by the combustion of 1 gram of alcohol within the chamber of the respiration calorimeter. In the bomb calorimeter all the water vapor formed is condensed within the apparatus, and hence the heat that had been required to vaporize the water is given off again. In the respiration calorimeter, on the other hand, the water passes out as vapor in the ventilating air current. The heat required to vaporize it comes from the combustion of the alcohol, and is not measured by the calorimeter. In order to obtain the total amount of heat given off in the combustion, therefore, the heat actually measured must be added to the amount required to vaporize the excess of water in the outgoing over that in the incoming air current, which is the amount of water vaporized at the expense of the heat produced in the combustion of the alcohol.

THE CALORIE HERE USED AS THE UNIT OF MEASURE.

Although the specific heat of water is often taken as unity for all temperatures, it actually varies by an appreciable amount. Hence if the unit of heat be defined as the amount required to raise unit mass of water 1 degree, this unit will be a variable one. The theoretical large calorie, namely, the quantity of heat that will raise a kilogram of water from 0° to 1° , or from 4° to 5° , is a very inconvenient unit in practice. Moreover, the specific heat of water changes quite rapidly at these low temperatures, and hence a higher temperature is more favorable for the working unit. Many authorities take the specific heat of water at 15° C. as unity. Inasmuch, however, as we have used 20° C. as our standard temperature for the respiration calorimeter in experiments with human subjects, and inasmuch also as the specific heat of water has a minimum near to 20° and changes very slowly in that vicinity, we have found it desirable to take as our working unit of heat the calorie at 20° . In other words, the large calorie at 20° , which we designate in the tables as C_{20} , is the amount of heat required to raise the temperature of a kilogram of water 1 degree at 20° C. (that is, from half a degree below 20° to half a degree above). The large calorie at any other temperature is here designated by C_t , and is the amount of heat required to raise the temperature of a kilogram of water 1 degree at the temperature t .

Since the specific heat of water is nearly a minimum at 20° C., our standard calorie, C_{20} , is nearly always less than C_t . This difference is ordinarily neglected. In experiment No. 6 with a man described beyond, in which work was performed, it might perhaps be neglected, since it is considerably less than some of the other errors of the experiment. But in the alcohol-test experiments and in the experiment with a human subject in which no work was performed, this difference is, relatively speaking, not inconsiderable. In Table 12 the specific heat of water is given for different temperatures between 0° and 31° . The

figures are based upon the experiments of Rowland,¹ Bartoli and Straciatini,¹ Griffiths,¹ and Ludin.² The differences in the results obtained by these investigators at temperatures below 22° are very small, and, in view of the care with which their experiments were made, we do not believe that the estimates of this table can be far enough from the truth materially to diminish their value for the present purpose.

TABLE 12.—*Specific heat of water at different temperatures referred to that at 20° C. as unity.*

Temperature ° C.	Specific heat.	Temperature ° C.	Specific heat.
0	1.0090	16	1.0007
1	1.0083	17	1.0004
2	1.0076	18	1.0002
3	1.0069	19	1.0001
4	1.0062	20	1.0000
5	1.0056	21	.9999
6	1.0050	22	.9998
7	1.0044	23	.9998
8	1.0039	24	.9998
9	1.0034	25	.9998
10	1.0029	26	.9998
11	1.0024	27	.9999
12	1.0020	28	.9999
13	1.0016	29	1.0000
14	1.0013	30	1.0001
15	1.0010	31	1.0002

It will be seen that at 0° the calorie (C_0) is nearly 1 per cent greater than C_{20} , and that C_{10} is about three parts in a thousand greater than C_{20} .

The results of all the combustions by the bomb calorimeter, as well as the measurements by the respiration calorimeter, are to be expressed in terms of C_{20} . To do this it is necessary to know the mean specific heat of water for the range of temperature employed in any given experiment. For example, if water is warmed from 3° to 17° in passing through the absorbing pipes of the respiration calorimeter, the result will be in terms of $C_{3.17}$; that is, in terms of the mean calorie from 3° to 17°. This is 1.0032 times as great as the standard calorie C_{20} , whereas C_{10} , the calorie for the mean temperature, is only 1.0029 times as great as C_{20} . In other words, the mean specific heat from 3° to 17° is 1.0032 times the specific heat at 20°, whereas the specific heat at 10°, the mean temperature, is 1.0029 times that at 20°. The difference between the mean specific heat for this range of temperature and the specific heat of the mean temperature is therefore appreciable; this is

¹ See p. 43.

² Inaug. Diss., Zurich, 1895; cited by Longuinine, Bestimmung der Verbrennungswärme, Berlin, 1897, p. 17. See discussion of results of experiments on the specific heat of water on pp. 12-20 of this valuable treatise.

of course because the variation of the specific heat is not linear. We have accordingly calculated the mean specific heat of the water in every case for the range of temperatures employed, and expressed the heat measured in terms of C_{20} . In the tables this range of temperature is given in the fourth column, and the heat in terms of C_{20} in the fifth column.

THE LATENT HEAT OF WATER VAPOR.

The value commonly used for the latent heat of vaporization of water at different temperatures is that given by Regnault¹ as the result of his classical investigations half a century ago. Regnault's method, for temperatures between 63° and 195° , consisted in condensing, within a suitable receptacle placed inside a water calorimeter, the vapor of water generated by ebullition in a separate boiler, the pressure in which could be varied from a small fraction of 1 atmosphere to 20 atmospheres or more. The quantity of heat yielded by the vapor upon condensation was determined by the increase of temperature of the water surrounding the condenser. The apparatus was large and very elaborate, and the investigation was carried out in a masterly manner. Regnault's formula, which expresses quite closely the results obtained throughout the given range of temperatures, i. e., from 63° to 195° , is $H = 606.5 + .305 t$. H represents what Regnault called the "total heat" of steam or water vapor, at the temperature t ; that is, it is the number of small calories required to raise a gram of water from 0° C. to any temperature t and then completely vaporize it at that temperature. For $t = 100^{\circ}$, this gives $H = 637$. The "latent heat of vaporization" at any temperature, as distinguished from the "total heat" at the same temperature, is the number of units of heat required to evaporate the water after it has been brought to the temperature of evaporation. Hence at 100° C. the latent heat of vaporization is 537 calories. The formula for the latent heat at any temperature t is

$$\begin{aligned} L &= H - t \\ \therefore L &= 606.5 + .305 t - t \\ \text{or } L &= 606.5 - .695 t \end{aligned}$$

Regnault's value for the latent heat of steam at 100° is abundantly confirmed by later researches. Andrews, Favre and Silberman, Berthelot and others obtain results very closely agreeing, and the accuracy of the determinations leaves little to be desired so far as this temperature is concerned.

At lower temperatures than 63° , however, this method was inapplicable because the change of state from water to steam at low pressure is irregular and explosive; hence a different method became necessary. The process was accordingly reversed, and water contained in a small reservoir inside a much smaller calorimeter than that previously

¹ Mém. Acad. Roy. Sci. Inst. France, 21 (1847), pp. 635-728.

used was evaporated at reduced pressure. The heat absorbed in the vaporization of the water (about 5 grams at each experiment) was then determined from the lowering of the temperature of the water which surrounded the vessel in which the evaporation took place. The results, as Regnault himself points out, were subject to comparatively large experimental errors, and were very discordant. The mean results over a range of temperature from 0° to 16° are fairly well represented by the formula given above for higher temperatures.

In the hope of obtaining better results at these low temperatures Regnault tried a third method.¹ This consisted in passing a current of air through a specially arranged receptacle containing water, and so carrying away the water vapor in air at external atmospheric pressure. The heat absorbed was determined, as before, by the lowering in temperature of the surrounding water. Correction was of course made for the heat yielded or absorbed by the air current itself, according as it left the calorimeter cooler or warmer than upon entering it. The air was not entirely saturated, and hence the circumstances of this experiment corresponded very closely to those under which water vapor is carried away from the interior of our respiration calorimeter. Regnault made only two series of experiments by this method, there being four experiments in the first series and three in the second. Unfortunately for our present purpose, the results obtained were very unsatisfactory. The mean of the first series gave $H=612.8$ for 16.5° , instead of 611.5 which the formula requires; and the mean of the second series gave 623.2 at 18° , instead of 612 as required by the formula. The individual determinations of the first series were 608.5 , 616.9 , 608.7 , 617.2 , thus presenting very large differences.

One reason for so large discrepancies appears to be the large cooling corrections to which the apparatus was subject. For example, in the first experiment the temperature of the water of the calorimeter dropped from 17.33° to 13.95° , a fall of 3.38° . But after applying the necessary corrections due to disturbing influences, the difference is reduced to 2.5873° . That is, about 25 per cent of the lowering of temperature was due to external disturbing causes, and it is hardly to be expected that such large corrections can be determined with sufficient accuracy.

Moreover, Regnault appears to have made a serious error in computing his results. In the formula given² X and τ are inadvertently interchanged. Making this correction, the formula expresses the value of the total heat in terms of the various quantities determined by the experiment. In the tabulated results,³ the total heat is recorded as the latent heat of vaporization, there called λ and then the "heat of the

¹ *Mém. Acad. Roy. Sci. Inst. France*, 26 (1862), pp. 883-890.

² *Ibid.*, p. 886.

³ *Ibid.*, pp. 888, 889.

water," numerically equal per gram to the mean temperature of the water at evaporation, is added again to give the values recorded as the total heat, called X . If the values of λ for the total heat are taken, as it appears to us should be done, the value for the latent heat of vaporization of water obtained by this third method are smaller than by the second method and smaller than the formula gives. However, the results are too discordant to be of much value, whether X or λ be taken as the total heat.

Starkweather,¹ in a critical review of various determinations of the latent heat of water vapor, quotes the work of Dieterici,² Griffiths,³ and Svensson⁴ as the best that has been done at low pressure and temperatures. Dieterici and Svensson determined with an ice calorimeter the latent heat of water vapor at 0°C . Dieterici's work is very carefully done, and his result is $L = 598.9$ at 0°C ., in terms of the quantity of heat required to raise 1 gram of water from 15° to 16° as the unit of heat. Svensson's result agrees very closely with this, being 599.9. Griffiths measured the latent heats of water vapor between 25° and 50°C ., and succeeds in representing them by the formula $L = 596.73 - .601 t$. Extrapolating to 0° and 100° , this agrees quite well with Dieterici at 0° and Regnault and others at 100° , being 596.73 at 0° and 536.6 at 100° . None of these experiments, however, have been carried out at the temperature commonly used in the respiration calorimeter—i. e., 20°C . Hence we are obliged to deduce the latent heat of vaporization at 20° from formulas given by experiments at other temperatures.

Using Regnault's original formula, from which $L = 606.5 - .695 t$ we get $L = 592.6$ at 20°C . Using Starkweather's modification of this formula, which agrees with Regnault's results at temperatures between 63° and 100° better than Regnault's, viz, $L = 598.9 - .558 t - .00064 t^2$, L becomes 587.5 at 20°C . Using Griffiths's formula above as quoted $L = 584.5$ at 20°C .

Some preliminary experiments have been made with the respiration calorimeter, with a view of determining this quantity L , i. e., the latent heat of vaporization of water at 20° , under the circumstances of the respiration experiment. The results so far have not, however, given a satisfactory value for this quantity. We have therefore taken 592 as a provisional value for the calculation of the experiments reported in this bulletin, and it would appear that this is probably within 1 per cent of the truth, although it is possibly as much as 2 per cent in error. Further investigations at 20° are necessary in order to fix the value more precisely.

¹"Concerning Regnault's calorie and our knowledge of the specific volumes of steam." Amer. Jour. Sci., 7 (1899), p. 13.

²Ann. Phys. u. Chem. [Wiedemann], 38, 1889.

³Phil. Trans. Roy. Soc. [London], A, 1895.

⁴Beiblätter, Ann. Phys. u. Chem. [Wiedemann], 20, p. 356.

In a preliminary publication¹ of results of these experiments the total heat of water vapor at 20° (i. e., 612) was taken by an oversight instead of the latent heat in computing the amount of heat carried away by the water vapor in the ventilating current of air. But inasmuch as the temperatures in the calculations for these experiments are all reduced to 20° C. instead of 0°, the heat above 20° should be used, which is of course the latent heat itself when the water vapor is carried away at 20° C.

ARRANGEMENTS FOR THE COMPLETE COMBUSTION OF ALCOHOL IN THE TEST EXPERIMENTS.

Various substances have been used by experimenters with different forms of respiration apparatus for burning within the chamber in order to deliver known quantities of carbon dioxide and water for the purpose of testing the accuracy of the apparatus and methods. The chief difficulty is to find substances which can be so burned as to insure complete oxidation of the carbon and hydrogen. The first attempts in this laboratory with the combustion of alcohol were unsatisfactory because the oxidation of the alcohol was incomplete, and a considerable amount of experimenting was necessary in order to learn the conditions under which complete combustion could be secured. As the result a small lamp, such as is ordinarily used with kerosene for illuminating purposes, has been employed. By proper arrangement of wick and chimney the alcohol is burned so completely that no traces of volatilized alcohol, acetone, aldehyde, carbon monoxide, or other substances capable of yielding carbon dioxide upon heating with oxygen could be found among the products of combustion.²

DESCRIPTION OF THE TEST EXPERIMENTS.

A considerable number of alcohol test experiments were made. The individual experiments included from one to seven periods or "runs" of approximately six hours each. Three of these tests are here described in detail in order to show how they were made and how the results were calculated. These three tests were made in the spring of 1897, each being followed by an experiment with a man in the chamber. The "work" experiment with a man, No. 6, described beyond, pages 74 to 87, was made between the second and third of these tests.

The lamps used in these tests contain approximately 380 grams of

¹ Connecticut Storrs Sta. Rpt. 1897, p. 212.

² Jour. Amer. Chem. Soc., 20 (1898) p. 293. The details of a considerable amount of experimental data accumulated upon this subject by Drs. F. G. Benedict and W. J. Karslake are reserved for future publication. It will suffice to say that a large number of preliminary experiments were made with various organic compounds of known purity and composition, and alcohol was selected because of the ease of securing complete combustion under proper conditions. The lamp and arrangements for burning the alcohol inside the chamber were the same as in the experiments where the combustion was proved to be complete.

alcohol. By adjusting the wick the rate of burning was so regulated as to give off carbon dioxid and water in the desired amounts. Under no circumstances was the flame allowed to have a luminous tip. Just before the beginning of each six-hour period of the test the lamp was filled, lighted, and the wick adjusted. The flame was then extinguished. After the lamp had cooled it was weighed, immediately put into the chamber, and lighted. The lamp was introduced into the chamber through the food aperture and was placed in a basket suspended from the ceiling of the chamber. When a change was made from one lamp to the other between the periods the ventilating air current was stopped, the cover removed from the food aperture, and the basket containing the lamp drawn close to the edge of the aperture by one attendant, while another reached in and removed the lamp, extinguishing it as soon as it was brought out. Another lamp was then placed in the basket, lighted, and the basket allowed to swing back to its normal position, the cover replaced on the food aperture, and the air current started again. The whole operation of removing one lamp and introducing the other, including shutting off and starting the air current, usually required less than a minute. The lamp that was removed was weighed at once, and the loss of weight was taken as the measure of the amount of alcohol burned during the period. In computing the amounts of heat given off by the combustion of the alcohol, allowance was made for the heat brought out of the chamber in the heated lamp chimney.

The lamp itself and its contents were not heated appreciably, excepting the metal burner, and the amount of heat carried away by the latter was very much less than by the chimney. Several determinations of the heat of the chimney were made by dropping it into the water contained in a calorimeter and noting the rise of temperature produced. The results ranged from about 1.5 to 2.5 large calories. Accordingly, the following estimates, which make a small allowance for the heat of the burner, are used as corrections in computing the results: For the maximum rate of burning, 2.5 large calories; for the mean rate of burning, 2 large calories, and for the minimum rate of burning, 1.5 large calories.

One of these numbers is to be added to the quantity of heat measured in each experimental period. This correction amounts to about three parts in a thousand of the heat measured. While this correction is itself not entirely satisfactory, the error can hardly be large enough to materially affect the result.

In Table 13 are shown the date and duration of each experiment and each period; the total amount of alcohol burned and the rate of combustion per hour; the number of liters of air in the ventilating air current; the data obtained for determining the amounts of carbon dioxid and water produced by the burning of the alcohol, and the comparison of the amounts thus determined with the theoretical amounts produced

by the oxidation of the same amounts of alcohol. The number of milligrams per liter of carbon dioxide in the incoming and in the outgoing air current, as sampled by the aspirators, is shown in the sixth and seventh columns. The difference between these quantities represents the excess in the outgoing air current—i. e., the amount added by the combustion of the alcohol to each liter of air in the ventilating air current. This excess per liter multiplied by the number of liters gives the total excess. The total amounts thus added are shown in the eighth column of the table. Similar data serve for the computation of the total excess of water in the outgoing air current not removed by the freezers. The amount of water condensed in the freezers added to the excess gives the total excess in the outgoing air current. This total excess is not shown in the table.

If the amounts of carbon dioxide and water in the air in the chamber at the end of a given experimental period are not the same as at the beginning, allowance must be made for the gain or loss of these compounds in calculating the amount produced by the combustion of the alcohol during the period. When the rate of combustion of the alcohol is quite constant, there is but little need of analyses of the residual air in the chamber at the beginning and end of each experimental period. In such an experiment as No. 3, however, where the rate of combustion was purposely made irregular in order more nearly to approach to the condition existing in experiments with men, analyses of the residual air are necessary. The ninth and sixteenth columns of Table 13 show the amounts of carbon dioxide and water found in the residual air of the chamber. Columns 10 and 17 of the table show the amounts actually measured, these amounts being corrected for differences in the residual amounts in the chamber when such determinations were made. With these values the theoretical amounts given off by the combustion of the alcohol during the different periods are compared. The results of the three tests reported in full are shown in the following table.

TABLE 13.—Amounts of carbon dioxide and water actually obtained by the combustion of different quantities of alcohol in the respiration calorimeter as compared with the theoretical amounts from the same quantities of alcohol.

Tests and periods.			Alcohol burned.			Carbon dioxide.				Water.								
Number and date.		Dura- tion.	Total.	Per hour.	Ventila- ting cur- rent.	In in- coming air per liter.	In outgoing air.		Resid- ual amount in cham- ber.	Deter- mined amount from alcohol burned.	Theoret- ical amount from alcohol burned.	In in- coming air per liter.	In outgoing air.		Resid- ual amount in cham- ber.	Deter- mined amount from alcohol burned.	Theoret- ical amount from alcohol burned.	
<i>Test 1.</i>																		
1897.																		
Period 1, Apr. 26	6	0	120.3	20.05	25.024	0.673	9.035	209.24	.....	209.24	208.67	0.853	1.038	4.63	139.6	.....	144.23	139.27
Period 2, Apr. 27	5	21	101.3	18.95	21.915	.899	8.707	172.43	.....	172.43	175.72	.951	.936	-0.33	116.5	.....	116.17	117.28
Period 3, Apr. 27	6	3	112.2	18.54	25.024	.675	8.604	198.43	.....	198.43	194.63	.893	.967	1.85	131.4	.....	133.25	129.89
Period 4, Apr. 27	5	58	104.3	17.50	25.024	.562	8.019	186.60	.....	186.60	180.92	.838	.914	1.90	121.5	.....	123.40	120.75
Period 5, Apr. 27	6	7	103.9	17.00	25.024	.642	7.758	178.07	.....	178.07	180.23	.885	.854	-0.77	120.5	.....	119.73	120.28
Period 6, Apr. 28	7	0	119.3	17.04	28.911	.566	7.657	205.00	.....	205.00	206.94	.828	.902	2.10	135.5	.....	137.60	138.12
Period 7, Apr. 28	4	17	71.0	16.58	18.176	.549	7.515	126.60	.....	126.60	123.15	.863	1.032	2.70	81.4	.....	84.10	82.20
Period 8, Apr. 28	5	56	119.2	20.10	25.175	.565	8.482	199.20	.....	199.20	206.76	.862	.972	2.77	127.6	.....	130.37	138.00
Period 9, Apr. 28	6	2	117.8	19.53	25.953	.614	8.513	204.93	.....	204.93	204.34	.789	.966	4.53	134.0	.....	138.53	136.38
Period 10, Apr. 29	5	55	111.8	18.90	25.174	.644	8.395	192.86	.....	192.86	193.93	.701	.843	3.55	128.8	.....	132.36	129.43
Period 11, Apr. 29	5	13	95.9	18.40	21.260	.721	8.517	165.95	.....	165.95	166.35	.897	1.003	2.24	108.1	.....	110.34	111.02
Total, 1 to 11	63	52	1,177.0	.....	266.660	.....	.....	2,039.31	.....	2,039.31	2,041.64	.....	.....	25.17	1,344.9	.....	1,370.07	1,362.62
Total, 3 to 11	52	31	955.4	.....	219.721	.....	.....	1,657.64	.....	1,657.64	1,657.25	.....	.....	20.87	1,088.8	.....	1,100.67	1,106.10
<i>Test 2.</i>																		
1897.																		
Period 1, May 10	5	56	157.9	26.62	25.236	.751	11.650	275.27	.....	275.27	273.90	1.208	1.329	3.03	182.6	.....	185.63	182.80
Period 2, May 10	6	0	147.7	24.62	24.769	.757	11.190	258.42	.....	258.42	256.20	1.172	1.320	3.66	174.6	.....	178.26	170.99
Period 3, May 10	6	0	160.8	26.80	24.802	1.132	12.168	273.71	.....	273.71	278.90	1.401	1.511	2.70	179.9	.....	182.60	186.16
Period 4, May 11	6	0	165.8	27.63	25.284	.626	12.052	288.88	.....	288.88	267.60	1.341	1.532	4.80	184.7	.....	189.50	191.95
Period 5, May 11	6	0	166.6	27.77	24.919	.680	12.241	288.16	.....	288.16	288.98	1.311	1.534	5.47	183.5	.....	188.97	192.87
Total	29	56	798.8	.....	125.010	.....	.....	1,384.44	.....	1,384.44	1,385.58	.....	.....	19.66	905.3	.....	924.96	924.77

The method of applying the data obtained by the analyses of residual air is briefly explained on page 38. For example, the quantities given in the ninth and sixteenth columns represent the amounts of carbon dioxid and water remaining in the apparatus at the beginning of the experiment and at the end of each period. There were 20.41 grams of carbon dioxid in the air of the chamber at the beginning of the first period of test 3, and 29.37 grams at the end. In other words ($29.37 - 20.41 =$) 8.96 grams of the carbon dioxid given off by the combustion of the alcohol during the period remained in the chamber at the close and must be added to the total excess of 117.62 grams found in the outgoing air in order to obtain a true measure of the amount produced in the chamber during this period, which is 126.58 grams. In a similar manner we find that during the fourth period the quantity of carbon dioxid in the chamber diminished by 15.02 grams, and this amount must therefore be deducted from the 179.46 grams total excess in the ventilating air current to obtain the determined amount given off by the combustion of the alcohol.

Similar calculations serve to show the amount of water vapor that was added to or removed from the air of the chamber during each period, and the corresponding amount that must be added to or deducted from the total excess of water in the outgoing air current (the sum of the amounts in columns 14 and 15 of Table 13). Thus the correct figure for the determination of the water given off by the combustion of the alcohol during the first period of the third test is $8.22 + 98.80 + (31.68 - 43.91)$, or 94.79 grams. It will be noticed that there was nearly twice as much water vapor in the chamber at the beginning of this test as at the end. The air at the beginning was comparatively moist, at the end unusually dry. The natural tendency of this condition would be to cause the evaporation, during the experiment, of some of the water that might have been condensed on the surface of the absorbers in the chamber. In experiments with man arrangements are made whereby the absorbers can be weighed, and it is not unusual to find a difference of over 100 grams in this weight during a six-hour period. It is quite probable that the excess of water found in this test was evaporated from the surface of the absorbers as the air became drier.

In the first of the test experiments there was some irregularity in the first two periods, so that two totals are given, one for the whole experiment and one in which these first two periods are omitted. The difference in the results is not, however, appreciable. Including the first two periods, 99.9 per cent of the carbon dioxid and 100.5 per cent of the water theoretically given off by the combustion of the alcohol were measured, while if the first two periods are excluded these percentages are 100 and 100.3, respectively. In the second test the agreement between the theoretical values and those measured was as close. The third test was not so satisfactory. More than the

theoretical amount of water was found in the air current, the amount being 101.1 per cent of that required. As was mentioned in the preceding paragraph, the excess of water determined in this test is probably due to the evaporation of some of that condensed on the absorbers at the beginning of the test, owing to the air becoming so much drier as the experiment progressed.

A transcript of a page of the record book in which the calorimetric data are recorded by the operator at the "observer's table" during the progress of one of the electrical check experiments was given in Table 1. A similar transcript of a page of the record made during the third of the alcohol check tests is given on page 67 (Table 14) as an illustration of the method of observing and recording the fundamental data. The table contains the record for two consecutive hours, the six columns on the left side being given to the first and those on the right side to the second hour.

The first three columns for each hour are similar to those in the record of the electrical tests. The fourth column for each hour gives the temperature of the air in the chamber, as determined by bridge No. 5. The fifth column gives the difference of temperature of the ingoing and outgoing current of water by bridge No. 6. The sixth column gives occasional pairs of readings of the mercury thermometers, the difference serving as a check upon the bridge readings. As before, the mercury thermometers are taken as the standard, and the bridge readings are corrected so as to agree with the differences of the mercury thermometers. In the table the differences are one, three, and two hundredths of a degree, and the average of all these differences for the entire experiment is used as the correction of the temperature as measured by the bridge. This was 0.03° , and in Table 15, which gives a summary of the heat measurements for one period of the experiment, this correction is applied to the average of the bridge readings of the third column. The temperature of the copper wall is given by thermometer No. 7, as previously described on page 27, the reading being placed under "Remarks," as it is taken only occasionally. Under No. 8 are the readings of the mercury thermometer, whose bulb is in a pocket of the copper wall. That the readings of Nos. 5, 7, and 8 are not the same is due to different positions of the "zero" points. This introduces no error, as only the change in temperature is desired, and this is given alike by all three.

TABLE 11.—Sample page from record book used for recording heat measurements, alcohol test experiment No. 3, May 27, 1897.

Time.	Inner walls.	Moving air.	Inside temper- ature.	Water by bridge.	Water ther- mometers.	Remarks.	Time.	Inner walls.	Moving air.	Inside temper- ature.	Water by bridge.	Water ther- mometers.	Remarks.
A. M. No. 1.	No. 4.	No. 5.	No. 6.	T ₁ , T ₂	No. 7, No. 8.	A. M.	No. 1.	No. 4.	No. 5.	No. 6.	T ₁ , T ₂	No. 7, No. 8.	
<i>h. m.</i>			°C.	°C.	°C.		<i>h. m.</i>			°C.	°C.	°C.	
2 00	1½	2	21.18	3.03	-----	21.56; 22.38	3 00	½	1	21.11	3.17	-----	21.50; 22.35
02	½	½	21.19	3.04	-----		02	½	1	21.12	3.16	-----	
04	0	½	21.19	3.07	-----		04	0	½	21.12	3.16	-----	
06	½	½	21.19	3.09	-----		06	0	½	21.13	3.18	-----	14.33
08	½	½	21.19	3.17	-----		08	½	½	21.13	3.19	-----	11.17
10	½	½	21.19	3.20	-----		10	½	0	21.13	3.19	-----	3.16
12	½	½	21.19	3.24	-----		12	½	½	21.13	3.19	-----	+ .03
14	1	½	21.19	3.22	-----		14	½	½	21.14	3.19	-----	
16	1½	½	21.19	3.24	-----		16	½	2	21.14	3.17	-----	
18	1½	0	21.19	3.35	-----	10 kilo-	18	½	½	21.14	3.18	-----	
20	2½	1	21.17	3.49	-----	grams at	20	½	½	21.14	3.18	-----	10 kilo-
22	2½	1	21.16	3.50	-----	2:20:35	22	½	½	21.15	3.20	-----	grams at
24	2½	½	21.15	3.50	-----		24	½	1	21.15	3.19	-----	3:22:32
26	1½	0	21.14	3.50	-----		26	½	½	21.15	3.18	-----	
28	1½	0	21.13	3.48	-----		28	½	0	21.15	3.18	-----	
30	1	1	21.13	3.39	-----		30	½	0	21.15	3.18	-----	
32	0	1	21.13	3.35	-----		32	½	½	21.15	3.20	-----	21.54; 22.38
34	½	1	21.12	3.35	-----		34	½	½	21.16	3.22	-----	
36	1	½	21.11	3.35	-----	14.39	36	½	½	21.16	3.23	-----	
38	1½	0	21.11	3.32	-----	11.08	38	½	0	21.16	3.26	-----	14.40
40	1½	½	21.11	3.32	-----	3.31	40	½	½	21.16	3.27	-----	11.14
42	1½	½	21.10	3.31	-----	+ .01	42	½	½	21.16	3.28	-----	3.26
44	2	½	21.10	3.31	-----		44	1½	½	21.16	3.30	-----	+ .02
46	2½	1	21.10	3.31	-----		46	2	0	21.16	3.28	-----	
48	2½	1	21.11	3.24	-----	10 kilo-	48	1½	½	21.16	3.27	-----	
50	2	½	21.11	3.23	-----	grams at	50	½	½	21.16	3.29	-----	10 kilo-
52	1½	0	21.10	3.20	-----	2:51:20	52	½	0	21.17	3.27	-----	grams at
54	1½	½	21.11	3.19	-----		54	1	1	21.17	3.28	-----	3:53:00
56	1½	½	21.11	3.17	-----		56	1	½	21.17	3.28	-----	
58	1½	½	21.11	3.17	-----		58	1	½	21.17	3.38	-----	
-----	24+21 9+10	-----	-----	-----	-----		-----	11½+10½	9+7	-----	-----	-----	

The method of calculating the amount of heat carried out of the apparatus by the water is illustrated by Table 15, which summarizes the results for the fifth period of the third alcohol test experiment. The number of minutes occupied in the escape of 10 kilograms of water is shown by the figures in the first column. The mean difference between the temperatures of the incoming and outgoing water current during each of these intervals is shown in the third column. These temperatures are, however, as measured by the bridge. Applying the correction of three-hundredths of a degree obtained from the comparison of the mercury and the copper thermometers above referred to, the corrected figures in the fourth column are obtained. These differences,

multiplied by the number of kilograms of water, show, in the fifth column, the number of calories of heat taken up by the water in its passage to the chamber—that is, the heat measured by the water current. These values are taken in terms of calories at the mean temperature of the water while it was in the calorimeter.

The figures in the last column show the temperature of the interior of the apparatus. It appears that this temperature was 21.12° at both the beginning and the end of the period; that is to say, the amount of heat in the metal walls and contiguous parts was the same at the beginning and end of the periods. There is, therefore, no correction to be applied for the heat capacity of the apparatus in this particular period.

TABLE 15.—Summary for one period of alcohol test experiment No. 3, May 27, 1897.

Calorimetric measurements.							Temperature of the inside by the copper thermometer No. 5.
(a) Time.	(b) Kilo-grams of water.	(c) Difference in temperature by bridge No. 6.	(d) Corrected difference of temperature, c — .03.	(e) Heat, b × d.			
<i>h.</i>	<i>m.</i>	<i>s.</i>	°C.	°C.	<i>Cals.</i>	°C.	
12	41	20				21.12	
12	47	45	2	3.82	3.79	7.58	21.14
1	18	49	10	3.63	3.60	36.00	21.14
1	49	45	10	2.86	2.83	28.30	21.18
2	20	35	10	3.14	3.11	31.10	21.17
2	51	20	10	3.36	3.33	33.30	21.11
3	22	32	10	3.18	3.15	31.50	21.15
3	53	00	10	3.24	3.21	32.10	21.17
4	24	10	10	3.38	3.35	33.50	21.11
4	54	45	10	3.27	3.24	32.40	21.11
5	26	03	10	3.26	3.23	32.30	21.14
5	57	00	10	3.35	3.32	33.20	21.14
6	28	06	10	3.37	3.34	33.40	21.11
6	42	17	4.6	3.22	3.19	14.67	21.12
379.35							

In Tables 16, 17, and 18 are given summaries of the heat measurements, by six hour periods, in three of the alcohol test experiments. The number of grams of water vaporized, as recorded in the eleventh column, is multiplied by .592 to give the "equivalent heat of water vaporized" in the twelfth column. The latter, added to "corrected heat measured," gives the "total heat" found. The number of grams of alcohol burned in each period, recorded in the third column, multiplied by 6.415, the number of calories produced by the combustion of 1 gram of the alcohol used, gives the number of calories that should have been produced in the alcohol flame. These are recorded in the fourteenth column as "calculated heat from alcohol burned."

TABLE 16.—Summary of the calorimetric measurements in alcohol test experiment No. 1, April 27–29, 1897.

1897.	Approximate period.	Alcohol burned.	Heat measured in terms of C_t to t_2 .	Range of temperature of water t to t_2 .	Heat measured reduced to C_{30} .	Change of temperature of calorimeter.	Capacity corrected by chimney.	Heat removed by chimney.	Corrected heat measured.	Water vaporized.	Equivalent heat of water vaporized.	Total heat found.	Calculated heat from alcohol burned.	Per cent measured.
		Gms.	Cals.	$^{\circ}C.$	Cals.	$^{\circ}C.$	Cals.	Cals.	Cals.	Gms.	Cals.	Cals.	Cals.	
Apr. 27	9 a.m. to 4 p.m.	112.2	633.7	3.2–13.7	636.1	+0.03	-1.8	2	636.3	133.3	78.9	715.2	719.8	.....
27	4 p.m. to 10 p.m.	104.3	581.6	3.7–13.3	583.7	+0.15	+9.0	2	594.7	123.4	73.0	667.7	669.1	.....
27	10 p.m. to 4 a.m.	103.9	590.6	3.9–13.3	592.8	-0.04	-2.4	2	592.4	119.7	70.9	663.3	666.5	.....
28	4 a.m. to 11 a.m.	119.3	669.2	3.8–13.3	671.7	+0.03	+1.8	2	673.5	137.6	81.5	757.0	765.2	.....
28	11 a.m. to 3 p.m.	71.0	402.1	3.4–13.9	403.6	-0.01	-0.6	2	405.0	84.1	49.8	454.8	455.5	.....
28	3 p.m. to 9 p.m.	119.2	670.2	2.7–14.1	672.8	-0.06	-3.6	2	671.2	130.4	77.2	748.4	764.7	.....
28	9 p.m. to 3 a.m.	117.8	663.0	2.9–14.0	665.5	-0.01	-0.6	2	666.9	138.5	82.0	748.9	755.7	.....
29	3 a.m. to 9 a.m.	111.8	628.3	3.0–13.6	630.7	0	0	2	632.7	132.4	78.4	711.1	717.2	.....
29	9 a.m. to 2 p.m.	95.9	541.2	3.1–13.5	543.4	0	0	2	545.4	110.3	65.3	610.7	615.2	.....
		955.4	5,379.9	.....	5,400.3	+0.03	+1.8	18	5,420.1	1,109.7	657.0	6,077.1	6,129.0	99.15

TABLE 17.—Summary of the calorimetric measurements in alcohol test experiment No. 2, May 10–11, 1897.

1897.	Approximate period.	Alcohol burned.	Heat measured in terms of C_t to t_2 .	Range of temperature of water t to t_2 .	Heat measured reduced to C_{30} .	Change of temperature of calorimeter.	Capacity corrected.	Heat removed by chimney.	Corrected heat measured.	Water vaporized.	Equivalent heat of water vaporized.	Total heat found.	Calculated heat from alcohol burned.	Per cent measured.
		Gms.	Cals.	$^{\circ}C.$	Cals.	$^{\circ}C.$	Cals.	Cals.	Cals.	Gms.	Cals.	Cals.	Cals.	
May 10	6 a.m. to 12 m.	157.9	888.4	3.2–13.3	891.7	0	0	2.5	894.2	185.6	109.8	1,004.0	1,012.9	.....
10	12 m. to 6 p.m.	147.7	836.8	3.7–13.4	840.0	+0.05	+3.0	2.5	845.5	178.3	105.6	951.1	947.5	.....
10	6 p.m. to 12 p.m.	160.8	936.2	3.7–13.7	939.7	-0.02	-1.2	2.5	941.0	182.6	108.1	1,049.1	1,061.5	.....
11	12 p.m. to 6 a.m.	165.8	964.0	3.8–13.6	967.6	0	0	2.5	970.1	189.5	112.2	1,082.3	1,063.6	.....
11	6 a.m. to 12 m.	166.6	964.3	3.5–13.4	968.0	-0.03	-1.8	2.5	968.7	189.0	111.9	1,080.6	1,068.7	.....
		798.8	4,580.7	.....	4,607.0	0	0	12.5	4,619.5	925.0	547.6	5,167.1	5,129.2	100.84

TABLE 18.—*Summary of the calorimetric measurements in alcohol test experiment No. 3, May 26-27, 1897.*

1897.	Approximate period.	Alcohol burned.	Heat measured in terms of C_1 to C_2 .	Range of temperature of water from t_1 to t_2 .	Heat reduced to C_{20} .	Change of temperature of calorimeter.	Capacity corrected by chimney.	Heat removed by chimney.	Corrected heat measured.	Water vaporized.	Equivalent of water vaporized.	Total heat found.	Calculated heat from alcohol burned.	Per cent measured.
		<i>Grams.</i>	<i>Cals.</i>	<i>C.</i>	<i>Cals.</i>	<i>C.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Grams.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>	
May 26	1 a. m. to 8 a. m.	72.5	402.8	15.5-17.5	403.0	-0.15	-9.0	1.5	395.5	94.8	56.1	451.6	465.0	.....
26	8 a. m. to 1 p. m.	94.6	537.6	4.3-8.6	540.1	-0.20	-12.0	2.5	530.6	104.6	61.9	592.5	606.9	.....
26	1 p. m. to 6 p. m.	108.0	626.1	7.0-12.0	628.1	-0.15	+9.0	2	639.1	127.9	75.7	714.8	692.8	.....
26	6 p. m. to 1 a. m.	91.3	493.0	11.1-15.2	493.8	+0.12	7.2	2	503.0	119.9	71.0	574.0	585.7	.....
27	1 a. m. to 7 a. m.	68.4	379.4	11.2-14.4	380.0	0	0	2	382.0	90.7	53.7	435.7	438.8	.....
27	7 a. m. to 1 p. m.	70.6	393.1	11.0-14.5	393.8	0	0	2	395.8	90.0	53.3	449.1	452.9	.....
		505.4	2,832.0	.....	2,838.8	-.408	-4.8	12.0	2,846.0	627.9	371.7	3,217.7	3,242.1	99.25

In Table 19 are summarized the principal results of all the alcohol check tests which were made up to the ninth, except the preliminary tests, in which the methods of manipulation were being worked out, and two tests the completion of which was prevented by accident. These individual experiments continued from 5 to 78 hours each, the total time being 317 hours. The rate of burning of the alcohol ranged from 10 to 27 grams per hour, and the strength of the alcohol from 90.26 to 90.77 per cent. Most of the tests were made in alternation with experiments with men, the object being to test the accuracy of the apparatus before and after each of the latter experiments.

TABLE 19.—*Summary of nine alcohol test experiments.*

No.	Date.	Duration.	Alcohol burned.			Carbon dioxide.			Water.			Heat.			
			Required.		Found.	Ratio of amount found to amount required.		Required.	Found.	Ratio of amount found to amount required.		Required.	Found.	Ratio of amount found to amount required.	
			Grams.	Per cent.	Grams.	Per cent.	Grams.	Per cent.	Grams.	Per cent.	Grams.	Per cent.	Calories.	Per cent.	
1897.															
1	April 27-29	52 31	455.4	1,657.2	1,657.6	100.0	1 106.1	1,109.7	100.3	6,129.0	6,077.1	99.15			
2	May 10 11	29 56	798.8	1,385.6	1,384.4	99.9	924.8	925.0	100.0	5,124.2	5,167.1	100.84			
3	May 26 27	33 50	505.4	876.7	887.8	101.3	585.1	627.9	107.3	3,242.1	3,217.7	99.25			
4	October 27 28	34 33	797.7	1,384.8	1,335.7	96.5	925.7	1,007.9	108.8	5,129.5	5,141.5	100.41			
5	November 2 3	35 09	788.2	1,365.1	1,376.7	100.8	912.3	929.8	102.0	5,048.4	5,050.0	100.03			
6	December 2	11 39	245.3	423.1	417.6	98.6	283.7	287.5	101.3	1,564.8	1,556.8	99.48			
1898.															
7	January 6	5 50	112.2	193.5	193.5	100.0	129.8	131.3	101.2	715.7	731.1	102.15			
8	January 24-27	77 57	1,607.8	2,784.4	2,769.7	99.5	1,899.8	1,881.6	101.1	10,394.7	10,268.5	99.74			
9	May 9	35 55	689.7	1,206.9	1,198.9	99.4	899.3	807.9	99.8	4,463.4	4,465.0	100.05			
Total a			9,892.5			9,886.2	99.9	6,026.8	6,063.8	100.6	41,762.8	41,675.8	99.93		

a Omitting the carbon dioxide and water in test No. 4 and the water in test No. 3.

It will be noticed that in No. 4 the determination of carbon dioxide was unsatisfactory, though we were unable to decide whether the error was due to imperfect sampling or other cause. The result is not included in the average of Table 19. The measurement of the heat was, however, very close to the theoretical value. Almost immediately after the close of this test another was made, in which all the results were very closely in accord with the theoretical values. If the determinations of carbon dioxide in test No. 4 are omitted, the maximum variation of the amounts determined from the theoretical amounts given off by the combustion of the alcohol was 1.4 per cent and the average variation only 0.1 per cent, or 1 part in 1,000 from the theoretical.

In tests Nos. 3 and 4 the determinations of water were unsatisfactory. We are inclined to attribute the errors to variations in the amounts of water condensed upon the absorbers. These results, like that for carbon dioxide in No. 4, are omitted from the averages. Omitting the determinations of water in tests Nos. 3 and 4, the maximum variation as actually determined from the theoretical amount was 1.2 per cent and the average variation only 0.6 per cent. In test No. 7 the proportion of heat measured was larger than usual. It will be observed, however, that this test continued only through one period of six hours. Some time is required to get the apparatus in temperature equilibrium, and the heat measurements of the first experimental period are frequently incorrect on this account. The omission of this experiment would not materially affect the total averages. Omitting this experiment, the maximum variation of the heat actually measured from the theoretical amount was 0.8 per cent and the average variation only 0.1 per cent.

SUMMARY OF TEST EXPERIMENTS.

The accuracy of the methods for the determination of carbon dioxide, water, and heat was tested by heat generated in the chamber by passing an electric current through a resistance coil and by burning ethyl alcohol within the chamber. In the electrical tests the measurements of heat generated and found were practically identical, the differences between the theoretical and actual results averaging about 0.1 per cent—that is, about 1 part in 1,000. In the alcohol tests the average amounts found by actual experiment were: For carbon, 99.9 per cent; hydrogen, 100.6 per cent; and heat, 99.9 per cent, respectively, of the theoretical amounts.

The determinations of carbon dioxide and water made by burning large quantities of alcohol in the respiration chamber agree reasonably well with each other and with the theoretical amounts. The variations, indeed, are not greater than are found in ordinary laboratory experience when alcohol is burned in the combustion furnace by the usual methods of organic analysis.

The agreement between the results given by the respiration calorimeter and the bomb calorimeter for the heat of combustion of alcohol, as shown in Table 35, is also very satisfactory when the great difference in the circumstances of the experiments is taken into consideration. In the bomb calorimeter a fraction of a gram of alcohol is absorbed in a

small block of cellulose or inclosed in a gelatin capsule and placed in a steel cylinder of perhaps half a liter capacity, which is filled with oxygen at a pressure of 20 atmospheres. An electric current passes through a fine iron wire, melts the latter, and ignites the alcohol, which is completely oxidized in an instant. The increase of temperature of the bomb and the water in which it is immersed gives the quantity of heat evolved, and from that the heat of combustion of a gram of alcohol is computed. In the respiration calorimeter, on the other hand, the alcohol contained in a small lamp burns quietly for many hours in a chamber ten thousand times as large as the bomb. Oxygen is supplied by a continuous current of air pumped through the apparatus, and a considerable portion of the heat of combustion is carried away in the latent heat of the water vapor produced. The sum of the heat measured by the calorimeter and the latent heat of the water vapor collected gives the total heat produced by the burning alcohol. That the average of a series of nine experiments should vary less than 0.1 per cent from the average of the determinations with the bomb calorimeter seems a gratifying result. Taken in connection with the electrical tests and the determinations of carbon dioxide and water already given, the results show that the respiration calorimeter is an instrument of precision and abundantly capable of doing the work for which it was designed.

EXPERIMENTS WITH A MAN.

The apparatus previously described was designed exclusively for experiments with human subjects. There were several reasons for beginning with men rather than with domestic animals. The study of human nutrition is very important. In the earlier development of the work, when many difficulties were to be overcome, it was very desirable to have inside the apparatus an intelligent person who could make and record important observations during the experiment, rather than an animal whose movements, even, could not be controlled. Indeed, the most advantageous way to develop methods and apparatus for experiments with animals is through such preliminary experience with men. The results of the experience thus far gained are now being utilized in planning apparatus and methods to be used not only with small animals, as rabbits, sheep, and dogs, but also with larger animals, as horses, oxen, and cows.

PLAN OF THE EXPERIMENTS.

The general plan of the experiments here described is the same as that of the respiration experiments previously reported.¹ For each experiment a diet is selected which furnishes the different nutrients in the amounts and proportions appropriate to the question under investigation. This diet is followed for eight days, of which the last four constitute the period of the experiment proper. In the first or preliminary period, of four days, the analyses of feces and urine are made, the data thus sufficing for a digestion and nitrogen metabolism experiment. On the evening of the fourth day the subject enters the

¹ U. S. Dept. Agr., Office of Experiment Stations Bul. 44.

respiration chamber, though the actual respiration calorimeter experiment does not begin until 7 o'clock on the morning of the fifth day. The night sojourn in the apparatus suffices to get the temperature of the apparatus and its content of carbonic acid and water into equilibrium, so that accurate measurements may begin with the morning of the fifth day and continue until 7 o'clock on the morning of the ninth day, thus making the duration of this experiment exactly four days. The determinations of carbon dioxid, water vapor, and heat are made in six-hour periods, so that the complete data for an experiment show the total amounts of these compounds given off from the body during the periods ending at 1 p. m., 7 p. m., 1 a. m., and 7 a. m. of each day of the experiment. The urine is also collected and the nitrogen determined for corresponding periods.

A definite schedule is planned before the commencement of the experiment, which is followed with reasonable closeness by the subject in the chamber and by those having the experiment in charge. The accompanying schedule or program shows the daily routine followed in each of the experiments here reported:

TABLE 20.—*Daily program of the rest and work experiments here reported.*

Time.	Rest experiment (No. 9).	Work experiment (No. 6).
7.00 a. m.	Rise	Rise.
	Pass urine	Pass urine.
	Weigh self, stripped	Weigh self, stripped and dressed.
	Weigh absorbers	Weigh absorbers.
	Collect drip	Collect drip.
7.45 a. m.	Breakfast	Breakfast.
		Weigh self.
8.20 a. m.		Begin work.
10.20 a. m.		10 minutes' rest.
10.30 a. m.	Drink 200 grams water	Weigh self; drink 200 grams water.
12.30 p. m.		Stop work.
1.00 p. m.	Pass urine	Pass urine.
		Collect drip.
	Collect drip	Weigh self.
	Weigh absorbers	Weigh absorbers.
1.15 p. m.	Dinner	Dinner.
		Drink 200 grams water.
		Weigh self.
1.50 p. m.		Begin work.
3.50 p. m.		10 minutes' rest.
4.00 p. m.	Drink 200 grams water	Weigh self; drink 200 grams water.
6.00 p. m.		Stop work; weigh self.
6.30 p. m.	Supper	Supper.
		Change underclothing.
		Weigh self, stripped and dressed.
7.00 p. m.	Pass urine	Pass urine.
	Collect drip	Collect drip.
	Weigh absorbers	Weigh absorbers.
10.00 p. m.	Drink 200 grams water	Weigh self.
	Weigh self, stripped	Drink 200 grams water.
	Retire	Retire.
1.00 a. m.	Pass urine	Pass urine.

In the rest experiment the subject was as quiet as he well could be. In the four days of the preliminary period he moved about but little and engaged in no considerable amount of either muscular or mental labor. During the four days passed in the chamber he was likewise quiet. The only muscular work done was that involved in dressing, putting up and taking down the folding chair, table, and bed, weighing himself and the absorbers, taking his meals, and caring for the excreta. He passed a large part of the time in reading and sleeping.

In the work experiment the subject was engaged in active muscular labor. The energy of the external muscular work done was entirely transformed into heat within the chamber. The larger part was first transformed into electrical energy by a small dynamo which was belted to the wheel of a stationary bicycle, and was then transformed into heat by an electric lamp through which the current passed. A small portion was transformed into heat by the friction of this bicycle dynamo or ergometer. The heat thus produced was measured with the heat given off from the body. The muscular work was continued for about eight hours per day, and the external muscular power as roughly measured by this ergometer was estimated to be equivalent to not far from 250 calories per day. This measurement was not as accurate as desirable and a special apparatus is now being constructed for the purpose. However, any error in measuring the work done does not affect the determination of the total energy since this is also measured by the calorimeter. It only affects the percentage found for the muscular work done—that is, the efficiency of the man as a machine.

All the furniture and bedding were weighed at the beginning and at the end of each experiment, but there was no appreciable change in weight. In the work experiment there was an apparent gain in weight of 20 grams in a total of 21,000, a number so small as to be within the limits of error in weighing.

In the analyses of the food, feces, and urine the methods employed were essentially those adopted by the Association of Official Agricultural Chemists,¹ with such modifications as experience and circumstances have shown desirable. The preparation, sampling, and analysis of the food materials was much the same as that described in a previous publication.²

In the rest experiment (No. 9) and those made later, most of the food materials were divided into portions proper for individual meals and put into jars. In this way the sampling was rendered more accurate and the labor involved in the preparation of the meals during an experiment was reduced to a minimum.

The treatment of the feces and urine was the same as that already described in the publication just referred to.

¹ U. S. Dept. Agr., Division of Chemistry Bul. 46.

² U. S. Dept. Agr., Office of Experiment Stations Bul. 44.

The heats of combustion of the food, feces, and urine were determined in the usual manner by means of the bomb calorimeter.¹

The determinations of carbon and hydrogen were made in the usual manner. The partially dried samples of food, feces, and urine were burned with cupric oxid with the aid of a current of oxygen, and the water absorbed by sulphuric acid, the carbon dioxid by potassium hydroxid. In some of the later experiments, as in No. 9, modifications of this method were employed, by which the time required for combustion was materially reduced. These modifications have not yet been described.

The percentage composition and heats of combustion of the food used in the two experiments here described, and of the feces for these experiments are shown in Table 21.

TABLE 21.—*Composition of food materials, etc.*

Laboratory No.	Food materials, etc.	Experiment No.	Nitrogen.	Carbon.	Hydrogen.	Water.	Protein (N. $\times$ 6.25).	Fat.	Carbohydrates.	Ash.	Heats of combustion per gram. ^a
			P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Cals.
2789	Beef, fried.....	6	4.77	21.28	3.05	60.3	29.8	8.7	.....	2.09	2.421
2835	Beef, cooked.....	9	4.10	16.35	2.25	67.3	25.6	5.4	.....	1.56	1.928
2788	Ham, deviled.....	6	2.64	35.67	4.48	42.2	16.5	36.9	.....	4.03	4.353
2790	Eggs.....	6	2.24	14.39	2.19	73.2	14.0	11.3	.....	.98	1.928
2793	Butter.....	6	.16	62.82	10.34	9.3	1.0	87.3	.....	2.39	7.954
2833	Do.....	9	.19	62.68	10.27	10.2	1.2	84.8	.....	3.80	7.761
2790	Milk, whole.....	6	.48	8.27	1.23	85.3	3.0	5.4	5.6	.69	.935
2836	Milk, skimmed.....	9	.52	4.04	.57	90.7	3.3	.1	5.2	.78	.393
2803	Bread, white.....	6	1.33	25.45	3.85	43.9	8.3	1.6	45.0	1.24	2.540
2834	Bread.....	9	1.34	24.53	3.54	44.7	8.4	.2	44.3	2.44	2.400
2830	Breakfast food, wheat.....	9	1.58	41.32	5.78	7.5	9.9	1.6	77.7	3.26	4.071
2829	Ginger snaps.....	9	.96	44.45	6.48	5.2	6.0	9.5	75.6	3.70	4.358
2831	Breakfast food, maize.....	9	1.78	44.34	6.45	5.6	11.1	8.7	71.1	3.46	4.444
2791	Beans, baked.....	6	1.15	12.44	1.73	71.4	7.2	.4	19.2	1.86	1.222
2792	Pears, canned.....	6	.05	7.01	1.18	81.4	.3	.2	17.9	.24	.759
2786	Sugar.....	6	.....	42.10	6.48	.....	.....	.....	100.0	.....	3.963
2832	Do.....	9	.....	42.10	6.48	.....	.....	.....	100.0	.....	3.960
2808	Feces.....	6	1.20	10.64	1.56	78.6	8.1	4.1	5.6	3.64	1.194
2838	Do.....	9	1.19	12.60	1.74	72.9	7.4	3.9	11.4	4.40	1.343

^a As determined.

EXPLANATION OF THE TABLES.

The results obtained in two experiments, Nos. 9 and 6 respectively, are shown in the following tables. Of these two experiments, No. 9 was a "rest" experiment, and was made in January, 1898. No. 6 was a "work" experiment, in which the subject rode the stationary bicycle

¹ For detailed description of improved forms of bomb calorimeter and accessory apparatus, see Connecticut Storrs Sta. Rpt. 1897, pp. 199-211.

about eight hours a day, and was carried on in May, 1897. Only such of the data are given here as it is believed will be sufficient for a clear understanding of the experiments. The order of the experiments is reversed to follow the more logical order of rest and work.

The daily diet in each of these two experiments was determined before the commencement of the preliminary period, and was followed throughout the eight days of the experiment, of which, as previously explained, the last four days were spent in the respiration chamber.

The daily menu in each experiment was as follows:

TABLE 22.—*Daily menu—rest experiment (No. 9).*

Breakfast.	Grams.	Dinner.	Grams.	Supper.	Grams.
Cooked beef.....	100	Cooked beef.....	150	Butter.....	15
Butter.....	15	Butter.....	20	Skimmed milk.....	390
Skimmed milk.....	160	Skimmed milk.....	210	Bread.....	25
Bread.....	25	Bread.....	50	Breakfast food, wheat.....	73
Breakfast food, maize.....	50	Breakfast food, wheat.....	50	Ginger snaps.....	60
Sugar.....	25	Sugar.....	25	Sugar.....	30
Coffee, about.....	300	Coffee, about.....	300	Coffee, about.....	300

TABLE 23.—*Daily menu—work experiment (No. 6).*

Breakfast.	Grams.	Dinner.	Grams.	Supper.	Grams.
Deviled ham.....	20	Cooked beef.....	100	Deviled ham.....	30
Boiled eggs.....	55	Butter.....	30	Butter.....	25
Butter.....	20	Milk.....	50	Milk.....	600
Milk.....	200	Bread.....	125	Bread.....	175
Bread.....	150	Baked beans.....	125	Sugar.....	15
Sugar.....	15	Canned pears.....	300	Coffee, about.....	300
Coffee, about.....	300	Sugar.....	20		
		Coffee, about.....	300		

Tables 24 and 25 show the amount of carbon dioxid eliminated in the rest and work experiments, respectively. The data reported show the number of liters of air in the ventilating air current and the milligrams per liter of carbon dioxid in the incoming and in the outgoing air during each six-hour period of the experiment. From these data the total excess of carbon dioxid in the outgoing over that of the incoming air is calculated. The analysis of the residual air in the apparatus at the close of each period gives data for the calculation of the increase or decrease of the carbon dioxid in the chamber at the end as compared with the beginning of each period. Applying this correction as explained on page 65, the actual elimination of carbon dioxid by the subject is obtained for each six-hour period. From this is calculated the total weight of carbon exhaled.

TABLE 24.—Record of carbon dioxid in rest experiment (No. 9).

Day.	Period.	Ventila- tion: number of liters of air.	Carbon dioxid per liter.			Total excess in out- going air.	Correc- tion for carbon dioxid in appa- ratus.	Cor- rected weight carbon dioxid exhaled by sub- ject.	Total weight carbon exhaled in carbon dioxid.
			In in- coming air.	In out- going air.	Excess in out- going air.				
		<i>Liters.</i>	<i>Mg.</i>	<i>Mgs.</i>	<i>Mgs.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>
1	7 a.m. to 1 p.m.	25,712	0.580	9.556	8.976	230.8	+ 3.1	233.9	63.8
	1 p.m. to 7 p.m.	25,987	.563	9.686	9.123	237.1	+14.9	252.0	68.7
	7 p.m. to 1 a.m.	26,785	.622	8.997	8.375	224.3	-14.7	209.6	57.2
	1 a.m. to 7 a.m.	26,065	.593	5.891	5.298	138.1	- 2.5	135.6	37.0
	Total.....	104,549	.....	.....	.....	830.3	+ .8	831.1	226.7
2	7 a.m. to 1 p.m.	27,057	.571	8.750	8.179	221.3	+11.3	232.6	63.4
	1 p.m. to 7 p.m.	25,878	.560	9.109	8.549	221.3	+ 5.3	226.6	61.8
	7 p.m. to 1 a.m.	26,652	.612	9.556	8.944	238.4	-12.6	225.8	61.6
	1 a.m. to 7 a.m.	26,011	.629	5.765	5.136	133.6	- 5.2	128.4	35.0
	Total.....	105,598	.....	.....	.....	814.6	- 1.2	813.4	221.8
3	7 a.m. to 1 p.m.	26,342	.624	9.139	8.515	224.3	+19.2	243.5	66.4
	1 p.m. to 7 p.m.	26,492	.721	9.349	8.628	228.6	+ .3	228.9	62.4
	7 p.m. to 1 a.m.	26,147	.722	9.326	8.604	225.0	-10.6	214.4	58.5
	1 a.m. to 7 a.m.	25,163	.727	5.917	5.190	130.6	- 8.1	122.5	33.4
	Total.....	104,144	.....	.....	.....	808.5	+ .8	809.3	220.7
4	7 a.m. to 1 p.m.	26,427	.710	8.973	8.263	218.4	+21.2	239.6	65.3
	1 p.m. to 7 p.m.	25,731	.735	9.525	8.790	226.2	+ .8	226.5	61.8
	7 p.m. to 1 a.m.	26,046	.636	10.021	9.385	244.5	-14.0	230.5	62.9
	1 a.m. to 7 a.m.	26,338	.612	5.870	5.258	138.5	- 9.1	129.4	35.3
	Total.....	104,542	.....	.....	.....	827.6	- 1.6	826.0	225.3
	Total, four days...	418,833	.....	.....	.....	.....	.....	3,279.8	834.5
	Average per day...	104,708	.....	.....	.....	.....	.....	819.9	223.6

TABLE 25.—Record of carbon dioxid in work experiment (No. 6).

Day.	Period.	Ventila- tion; number of liters of air.	Carbon dioxid per liter.			Total excess in out- going air.	Correc- tion for carbon dioxid in appa- ratus.	Cor- rected weight carbon dioxid exhaled by sub- ject.	Total weight carbon exhaled in carbon dioxid.
			In in- coming air.	In out- going air.	Excess in out- going air.				
		<i>Liters.</i>	<i>Mg.</i>	<i>Mgs.</i>	<i>Mgs.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>
1	7 a. m. to 1 p. m.	25,329	0.905	17.190	16.285	412.5	+69.9	482.4	131.57
	1 p. m. to 7 p. m.	21,497	.994	23.520	22.526	484.2	+11.4	495.6	135.17
	7 p. m. to 1 a. m.	22,274	.771	13.769	12.998	289.5	-52.2	237.3	64.72
	1 a. m. to 7 a. m.	22,173	.730	7.435	6.705	148.7	-29.6	119.1	32.50
	Total.....	91,273	.....	.....	.....	1,334.9	- .5	1,334.4	363.96
2	7 a. m. to 1 p. m.	23,364	.710	15.263	14.553	340.0	+ 76.4	416.4	113.55
	1 p. m. to 7 p. m.	23,356	.647	20.613	19.966	466.3	- 3.8	462.5	126.17
	7 p. m. to 1 a. m.	23,999	.587	13.651	13.064	313.5	-60.6	252.9	68.97
	1 a. m. to 7 a. m.	23,541	.606	6.381	5.775	136.0	-13.4	122.6	33.40
	Total.....	94,260	.....	.....	.....	1,255.8	- 1.4	1,254.4	342.09
3	7 a. m. to 1 p. m.	23,147	.516	16.143	15.627	361.7	+90.5	452.2	123.35
	1 p. m. to 7 p. m.	23,044	.612	21.070	20.458	471.4	-33.8	437.6	119.35
	7 p. m. to 1 a. m.	22,423	.912	13.474	12.562	281.6	-41.1	240.5	65.60
	1 a. m. to 7 a. m.	23,344	.678	6.925	6.247	145.8	-10.4	135.4	36.94
	Total.....	91,958	.....	.....	.....	1,260.5	+ 5.2	1,265.7	345.24

TABLE 27.—*Record of water in work experiment (No. 6).*

Day.	Period.	Ventilation; number of liters of air.	Water per liter.			Total excess in out- going air.	Con- densed in freez- ers.	Con- densed in cham- ber.	Correc- tion for water vapor in cham- ber.	Total water exhaled.
			In in- coming air.	In out- going air.	Excess in out- going air.					
		<i>Liters.</i>	<i>Mgs.</i>	<i>Mgs.</i>	<i>Mgs.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>	<i>Grams.</i>
1	7 a.m. to 1 p.m.	25,329	1.164	1.369	0.205	5.2	279.1	483.2	+3.7	.....
	1 p.m. to 7 p.m.	21,497	.955	1.546	.591	12.2	272.4	719.9	+6.6	.....
	7 p.m. to 1 a.m.	22,274	1.055	1.273	.218	4.8	282.1	.....	— .7	.....
	1 a.m. to 7 a.m.	22,173	.752	1.090	.338	7.5	247.3	199.8	—9.7	.....
	Total	91,273	.....	.....	.....	29.7	1,080.9	1,402.9	— .1	2,513.4
2	7 a.m. to 1 p.m.	23,364	.806	1.129	.323	7.5	258.3	445.5	+5.3	.....
	1 p.m. to 7 p.m.	23,356	.938	1.269	.331	7.7	284.2	556.0	+3.0	.....
	7 p.m. to 1 a.m.	23,999	.914	1.335	.421	10.1	298.9	.....	— .3	.....
	1 a.m. to 7 a.m.	23,541	.777	1.089	.312	7.2	267.9	81.0	—6.9	.....
	Total	94,260	.....	.....	.....	32.5	1,109.3	1,082.5	+1.1	2,225.4
3	7 a.m. to 1 p.m.	23,147	.824	1.352	.528	12.1	264.3	504.6	—6.0	.....
	1 p.m. to 7 p.m.	23,044	.900	1.371	.471	10.8	281.6	575.5	+9.8	.....
	7 p.m. to 1 a.m.	22,423	.710	1.164	.454	10.2	280.9	.....	— .7	.....
	1 a.m. to 7 a.m.	23,344	.848	1.171	.323	7.6	273.1	85.3	—3.3	.....
	Total	91,958	.....	.....	.....	40.7	1,099.9	1,165.4	— .2	2,305.8
4	7 a.m. to 1 p.m.	23,268	.798	1.134	.336	7.8	258.7	251.9	+5.8	.....
	1 p.m. to 7 p.m.	23,031	1.124	1.361	.237	5.5	280.4	560.6	—6.7	.....
	7 p.m. to 1 a.m.	23,833	.793	1.123	.330	7.9	295.0	.....	—3.6	.....
	1 a.m. to 7 a.m.	25,757	.870	1.042	.172	4.4	291.7	118.0	—3.1	.....
	Total	95,889	.....	.....	.....	25.6	1,125.8	930.5	—7.6	2,074.3
	Total, four days	373,380	.....	.....	.....	128.5	4,415.9	4,581.3	.....	9,118.9
	Avg. per day	93,345	.....	.....	.....	.....	.....	.....	.....	2,279.7

The calorimetric results in the two experiments are shown in Tables 28 and 29. The details of the table and methods of computation are as explained above in the description of the test experiments in which alcohol was burned in the respiration chamber.

TABLE 28.—*Summary of calorimetric measurements—Rest experiment (No. 9).*

Day.	Period.	Heat meas- ured.	Change of tem- pera- ture of calorim- eter.	Capac- ity correc- tion.	Correc- tion due to tem- perature of food and dishes.	Corrected heat.	Water vapor- ized.	Equiv- alent heat of water vapor- ized.	Total heat.
		<i>Cals.</i>	<i>°C</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Grams.</i>	<i>Cals.</i>	<i>Cals.</i>
1	7 a.m. to 1 p.m.	547.9	+0.12	+7.2	—22.2	532.9	217.9	129.0	661.9
	1 p.m. to 7 p.m.	556.6	— .12	—7.2	—37.5	511.9	241.7	143.1	655.0
	7 p.m. to 1 a.m.	472.7	— .05	—3.0	0	469.7	248.6	147.1	616.8
	1 a.m. to 7 a.m.	277.3	— .03	—1.8	0	275.5	233.7	138.4	413.9
	Total	1,854.5	.....	—4.8	—59.7	1,790.0	.....	557.6	2,347.6
2	7 a.m. to 1 p.m.	490.7	+ .04	+2.4	—22.9	470.2	224.2	132.7	602.9
	1 p.m. to 7 p.m.	489.2	+ .08	+4.8	—28.3	465.7	224.5	132.9	598.6
	7 p.m. to 1 a.m.	497.4	— .15	—9.0	0	488.4	243.3	144.1	632.5
	1 a.m. to 7 a.m.	289.2	+ .15	+9.0	0	298.2	221.3	131.0	429.2
	Total	1,766.5	.....	+7.2	—51.2	1,722.5	.....	540.7	2,263.2

TABLE 28.—Summary of calorimetric measurements—Rest experiment (No. 5)—(Cont'd.)

Day.	Period.	Heat measured.	Change of temperature of calorimeter.	Capacity correction.	Correction due to temperature of food and dishes.	Corrected heat.	Water vaporized.	Equivalent heat of water vaporized.	Total heat.
		<i>Cals.</i>	<i>°C</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Grams.</i>	<i>Cals.</i>	<i>Cals.</i>
3	7 a. m. to 1 p. m.	524.6	+ .08	+ 4.8	— 21.2	508.2	216.7	128.3	636.5
	1 p. m. to 7 p. m.	512.1	+ .08	+ 4.8	— 31.8	485.1	219.8	130.1	615.2
	7 p. m. to 1 a. m.	486.6	— .18	— 10.8	0	475.8	239.7	141.9	617.7
	1 a. m. to 7 a. m.	296.1	+ .10	+ 6.0	0	302.1	220.9	130.8	432.9
	Total.....	1,819.4	.....	+ 4.8	— 53.0	1,771.2	.....	531.1	2,302.3
4	7 a. m. to 1 p. m.	503.3	— .05	— 3.0	— 21.3	479.0	222.4	131.7	610.7
	1 p. m. to 7 p. m.	536.4	+ .05	+ 3.0	— 29.2	510.2	220.3	130.4	640.6
	7 p. m. to 1 a. m.	497.5	— .10	— 6.0	0	491.5	244.7	144.9	636.4
	1 a. m. to 7 a. m.	290.7	+ .04	+ 2.4	0	293.1	245.0	145.0	438.1
	Total.....	1,827.9	.....	— 3.6	— 50.5	1,773.8	.....	552.0	2,325.8
	Total, four days.....	7,268.3	.....	+ 3.6	— 214.4	7,057.5	.....	2,181.4	9,238.9
	Avg. per day.....	1,817.1	.....	+ .9	— 53.6	1,764.4	.....	545.3	2,309.7

TABLE 29.—Summary of calorimetric measurements—Work experiment (No. 6).

Day.	Period.	Heat measured.	Change of temperature of calorimeter.	Capacity correction.	Correction due to temperature of food and dishes.	Corrected heat.	Water vaporized.	Equivalent/heat of water vaporized.	Total heat.	Work done.		Heat equivalent.
										Duration.	Rate.	
		<i>Cals.</i>	<i>°C</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Gms.</i>	<i>Cals.</i>	<i>Cals.</i>	<i>Mins.</i>	<i>Watts</i>	<i>Cals.</i>
1	7 a. m. to 1 p. m.	1,157.3	+0.50	+30	— 11.7	1,175.6	284.3	168.3	1,343.9	238	42	143
	1 p. m. to 7 p. m.	1,270.7	— .10	— 6	— 28.8	1,235.9	284.5	168.4	1,404.3	216	41	127
	7 p. m. to 1 a. m.	617.7	— .25	— 15	.....	602.7	286.9	169.9	772.6	.....	.....	.....
	1 a. m. to 7 a. m.	298.1	— .00	— 00	.....	298.1	254.8	150.8	448.9	.....	.....	.....
	Total.....	3,343.8	.....	+ 9	— 40.5	3,312.3	1,110.5	657.4	3,969.7	.....	.....	270
2	7 a. m. to 1 p. m.	1,023.4	+ .15	+ 9	— 7.5	1,024.9	265.8	157.3	1,182.2	210	39	115
	1 p. m. to 7 p. m.	1,153.9	+ .05	+ 3	— 24.2	1,132.7	291.9	172.8	1,305.5	210	39	115
	7 p. m. to 1 a. m.	588.1	— .05	— 3	.....	585.1	309.0	182.9	768.0	.....	.....	.....
	1 a. m. to 7 a. m.	259.8	— .17	— 10	.....	249.8	275.1	162.9	412.7	.....	.....	.....
	Total.....	3,025.2	.....	— 1	— 31.7	2,992.5	1,141.8	675.9	3,668.4	.....	.....	230
3	7 a. m. to 1 p. m.	1,119.6	— .13	— 8	— 16.0	1,095.6	276.4	163.6	1,259.2	236	40	135
	1 p. m. to 7 p. m.	1,121.2	+ .06	+ 3	— 31.9	1,092.3	292.5	173.2	1,265.5	244	38	133
	7 p. m. to 1 a. m.	588.8	+ .06	+ 4	.....	592.8	291.1	172.3	765.1	.....	.....	.....
	1 a. m. to 7 a. m.	261.5	— .12	— 7	.....	254.5	280.6	166.1	420.6	.....	.....	.....
	Total.....	3,091.1	.....	— 8	— 47.9	3,035.2	1,140.6	675.2	3,710.4	.....	.....	268
4	7 a. m. to 1 p. m.	1,018.6	+ .13	+ 8	— 10.2	1,016.4	266.5	157.8	1,174.2	224	39	125
	1 p. m. to 7 p. m.	1,059.7	+ .10	+ 6	— 19.2	1,046.5	285.9	169.2	1,215.7	240	38	130
	7 p. m. to 1 a. m.	521.7	— .07	— 4	.....	517.7	302.9	179.3	697.0	.....	.....	.....
	1 a. m. to 7 a. m.	297.6	— .05	— 3	.....	294.6	296.1	175.3	469.9	.....	.....	.....
	Total.....	2,897.6	.....	+ 7	— 29.4	2,875.2	1,151.4	681.6	3,556.8	.....	.....	255
	Total, four days.....	12,357.7	.....	+ 7	— 149.5	12,215.2	4,544.3	2,690.1	14,905.3	.....	.....	1,023
	Avg. per day.....	3,089.4	.....	.....	.....	3,053.8	1,136.1	672.5	3,726.3	.....	.....	256

As has been previously mentioned, the urine was collected in six-hour periods beginning at 7 a. m. (the hour of beginning and ending the experiment). The amount of nitrogen in the urine from 7 a. m. of one day to 7 a. m. next day is taken as a measure of the protein metabolized during this period. Of course this makes no allowance for the nitrogen lag, but, as explained on page 93, it was considered that the error thus introduced might be ignored, since the subject had been living on the same diet and had had the same exercise from day to day for the experimental period of four days and the previous four days of the preliminary experiment also. The amount of nitrogen in the urine for 12 to 24 hours after the close of the experiment was also determined in six-hour periods, although these values are not recorded here. In Table 30 is summarized the amount of urine for each day of the rest and the work experiments, together with the percentage and amounts of nitrogen and carbon and the heat of combustion per gram, and the total heat of combustion of the urine.

TABLE 30.—*Amount and composition of urine.*

Experiment and day.	Amount.	Nitrogen.		Carbon.		Heat of combustion.	
						Per gram.	Total.
Rest experiment (No. 9):	<i>Grams.</i>	<i>Per cent.</i>	<i>Grams.</i>	<i>Per cent.</i>	<i>Grams.</i>	<i>Calories.</i>	<i>Calories.</i>
First day.....	1,855.3	1.01	18.75	0.69	12.80	0.082	152
Second day.....	1,977.6	.95	18.75	.65	12.79	.081	160
Third day.....	1,510.6	1.21	18.28	.83	12.50	.095	143
Fourth day.....	1,358.9	1.32	17.89	.90	12.19	.102	139
Total, four days.....	6,702.4	.....	73.68	.....	50.28	.....	594
Average per day.....	1,675.6	.....	18.42	.....	12.57	.....	149
Work experiment (No. 6):							
First day.....	1,349.9	1.27	17.17	.97	13.12	.094	127
Second day.....	1,109.4	1.48	16.39	1.13	12.54	.119	132
Third day.....	1,033.8	1.47	15.22	1.13	11.72	.115	119
Fourth day.....	1,304.7	1.25	16.34	.96	12.50	.094	123
Total, four days.....	4,797.8	.....	65.12	.....	49.88	.....	501
Average per day.....	1,199.4	.....	16.28	.....	12.47	.....	125

The data previously given serve for the calculation of Tables 31 and 32, which show the gain or loss of nitrogen, carbon, protein, and fat and the comparison of the estimated heat of the material oxidized in the body with the heat actually measured in the rest and work experiments. The calculations are partially explained by the letters and algebraic formula at the top of the columns. Thus column *d* indicates the gain or loss of nitrogen, and is computed by adding the amounts in the feces and urine, as shown in columns *b* and *c*, and subtracting this sum from the amount in the food as shown in column *a*.¹ In Table 32

¹ For further explanations of these calculations see U. S. Dept. Agr., Office of Experiment Stations Bul. 44.

the values given in columns *n*, *o*, and *p* are actual heats of combustion as determined by the bomb calorimeter. The values in columns *q* and *r* are obtained by the use of factors representing the average heat of combustion of 1 gram of protein and fat, respectively. The values in column *t* are obtained from Tables 28 and 29.

TABLE 31.—Income and outgo of nitrogen and carbon, with estimated gain or loss of protein and fat.

Experiment and day.	Nitrogen.					Carbon.					K.			m. Fat gain (+) loss (-)
	a. In food.	b. In feces.	c. In urine. ¹	d. Gain (+) loss (-)	e. Pro- tein gain (+) loss (-)	f. In food.	g. In feces.	h. In urine.	i. In respir- atory prod- ucts.	j. Gain (+) loss (-)	k. Car- bon in protein gained (+) or lost (-)	l. Car- bon in fat gained (+) or lost (-)		
				$= a -$ $(b+c).$	$= d \times$ 6.25.				$= j -$ $(g+h$ $+ i).$	$= e \times$ 0.53.	$= j - k.$			
<i>Rest experi- ment (No. 9).</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	<i>Gms.</i>	
First day . . .	19.1	1.2	18.7	-0.8	- 5.0	261.5	13.3	12.8	226.7	+ 8.7	- 2.7	+ 11.4	- 14.0	
Second day . .	19.1	1.3	18.8	-1.0	- 6.3	261.6	13.4	12.8	221.8	+ 13.6	- 3.3	+ 16.9	- 22.1	
Third day . . .	19.1	1.2	18.3	-. 4	- 2.5	261.5	13.3	12.5	220.7	+ 15.0	- 1.3	+ 16.3	+ 21.3	
Fourth day . .	19.1	1.3	17.9	-. 1	- 0.6	261.6	13.4	12.2	225.3	+ 10.7	-. 3	+ 11.0	+ 14.4	
Total	76.4	5.0	73.7	-2.3	-14.4	1,046.2	53.4	50.3	894.5	+ 48.0	- 7.6	+ 55.6	+ 72.7	
Average per day	19.1	1.2	18.4	-. 6	- 3.6	261.5	13.3	12.6	223.6	+ 12.0	- 1.9	+ 13.9	+ 18.2	
<i>Work experi- ment (No. 6).</i>														
First day	19.1	1.5	17.5	+0.1	+ 0.6	336.7	12.3	13.1	364.0	- 52.7	+ 0.3	- 53.0	- 69.3	
Second day . . .	19.1	1.5	16.6	+1.0	+ 6.2	336.7	12.4	12.6	342.1	- 39.4	+ 3.3	- 33.7	- 44.1	
Third day	19.1	1.5	15.4	+2.2	+13.8	336.7	12.3	11.7	345.2	- 32.5	+ 7.3	- 39.8	- 52.0	
Fourth day . . .	19.1	1.5	16.5	+1.1	+ 6.9	336.7	12.4	12.5	329.4	- 17.6	+ 3.7	- 21.3	- 27.8	
Total	76.4	6.0	66.0	+4.4	+27.5	1,346.8	49.4	49.9	1,380.7	- 133.2	+ 14.6	- 147.8	- 193.2	
Average per day	19.1	1.5	16.5	+1.1	+ 6.9	336.7	12.4	12.5	345.2	- 33.3	+ 3.6	- 36.9	- 49.3	

¹ Including nitrogen of perspiration.

TABLE 32.—Income and outgo of energy.

Energy (heats of combustion).								
Experiment and day.	Actually determined.			Estimated.			t. Heat actual- ly meas- ured.	Ratio of heat measured to that of material actually oxidized $t \div s$.
	<i>n</i> . Of food.	<i>o</i> . Of feces.	<i>p</i> . Of urine.	<i>q</i> . Of pro- tein gain- ed (+) or lost (—) $=e \times 5.5$.	<i>r</i> . Of fat gained (+) or lost (—) $=m \times 94$.	<i>s</i> . Of mate- rial actu- ally oxi- dized in body $=n - (o +$ $p + q + r)$.		
	Calories.	Calories.	Calories.	Calories.	Calories.	Calories.			Calories	Per cent.
<i>Rest experiment</i> (No. 9).								
First day	2,717	142	152	— 27	+ 140	2,310	2,348	.....
Second day	2,717	142	160	— 35	+ 208	2,242	2,263	.....
Third day	2,717	142	143	— 14	+ 200	2,246	2,302	.....
Fourth day	2,717	142	139	— 3	+ 135	2,304	2,326	.....
Total	10,868	568	594	— 79	+ 683	9,102	9,239	.....
Avg. per day .	2,717	142	149	— 20	+ 171	2,275	2,310	101.5
<i>Work experiment</i> (No. 6).								
First day	3,678	139	127	+ 3	— 651	4,060	3,970	.....
Second day	3,678	139	132	+ 34	— 415	3,788	3,668	.....
Third day	3,678	139	119	+ 76	— 489	3,833	3,710	.....
Fourth day	3,678	139	123	+ 38	— 261	3,639	3,557	.....
Total	14,712	556	501	+151	—1,816	15,320	14,905	.....
Avg. per day...	3,678	139	125	+ 38	— 454	3,830	3,726	97.3

SUMMARY OF RESULTS OF EXPERIMENTS WITH A MAN.

The results of the two experiments reported above are summarized in the following tables. Table 33 shows the balance of income and outgo of nitrogen and carbon, and the calculated gain or loss of protein and fat. Table 34 shows the daily income and outgo of protein and energy.

TABLE 33.—Average daily income and outgo of nitrogen and carbon in the rest and work experiments (Nos. 9 and 6), with the estimated gain or loss of protein and of fat.

Experiment.	Nitrogen.				Carbon.				Calculated gain or loss.		
	In food.	In feces.	In urine.	Gain (+) or loss (—).	In food.	In feces.	In urine.	In respiratory products.	Gain (+) or loss (—).	Of protein.	Of fat.
	Gms.	Gms.	Gms.	Gms.	Gms.	Gms.	Gms.	Gms.	Gms.	Gms.	Gms.
Rest (No. 9)	19.1	1.2	18.4	— 0.6	261.5	13.3	12.6	223.6	+12.0	—3.6	+18.2
Work (No. 6)	19.1	1.5	16.5	+ 1.1	336.7	12.4	12.5	345.2	—33.3	+6.9	—48.3

TABLE 34.—*Comparison of daily income and outgo of protein and of energy in the rest and work experiments (Nos. 9 and 6).*

Experiment.	Protein.		Energy.			
	Of food.	Actual-ly oxidized.	Of food.	Of material actual-ly oxidized.	Meas-ured.	Difference in per cent of heat of material actual-ly oxidized.
	Gms.	Gms.	Cals.	Cals.	Cals.	Per cent.
Rest (No. 9)	119.4	115.0	2,275	2,354	2,310	+1.5
Work (No. 6)	119.4	103.1	3,830	3,864	3,726	-2.7

The difference between income and outgo of energy in experiment No. 9 amounts to 1.5 per cent and in experiment No. 6 to 2.7 per cent of the energy of the material oxidized. This discrepancy may be due to experimental errors, of which several are possible, as pointed out on pages 90 to 94.

There was one source of error of special consequence in experiment No. 6. The muscular work of the subject was at times rather severe. As a consequence, heat was developed within the apparatus at a rapid rate and the changes in temperature within the chamber were considerable. We are inclined to think that the heat measurements under these circumstances were less accurate than usual, and that minor modifications of the apparatus may be needed to provide for greater accuracy in experiments of this class.

In later experiments, which are not yet reported, the differences between income and outgo of energy range much nearer to the theoretical; in other words, in these more accurate experiments not far from 99 per cent of the potential energy of the material metabolized and oxidized in the body is accounted for in the kinetic energy given off in the forms of heat and external muscular work.

In how far this fairly close agreement is due to a counterbalancing of errors it is impossible to say. But in view of the physiological difficulties in the way of absolutely accurate results, and the evident possibility of minor errors in the purely chemical and physical determinations, and likewise in the factors used for computation, this agreement seems to us very satisfactory. We believe that it marks a stage in the development of the apparatus and methods sufficient to warrant extended series of experiments upon various questions connected with the laws of nutrition, and such experiments have been begun. Efforts are being made at the same time to eliminate part at least of the experimental errors. At present these efforts are chiefly in the direction of improvement of methods of sampling and analyzing the food materials and excretory products, and finding of minor sources of error in the determination of carbon, hydrogen, and heat given off in the respiration chamber, and the direct determination of the oxy-

CORRECTION.

Please correct figures in the third and fourth columns of Table 34, p. 86, Bulletin 63, Office of Experiment Stations, United States Department of Agriculture, as follows:

Of food.	Of material actually oxidized.
<i>Cals.</i>	<i>Cals.</i>
2,717	2,275
3,678	3,830

gen of income and outgo. Minor alterations are also being made in the apparatus and the methods of its manipulation by which it is hoped that somewhat greater accuracy may be secured.

GENERAL SUMMARY.

The attempt has been made in the preceding pages to describe (1) a new form of respiration calorimeter and the methods of its use, and (2) several experiments in which the apparatus and methods have been employed.

The experiments here described had a twofold purpose: To test the accuracy of the apparatus and methods, and to determine the balance of income and outgo of matter and energy in the body. They are preliminary to more extended research upon some of the fundamental problems of nutrition.

The name here used for the apparatus, "respiration calorimeter," is suggested by the fact that it is essentially a respiration apparatus with appliances for calorimetric measurements. As a respiration apparatus it is similar in principle to that of Pettenkofer. The calorimeter is essentially a water calorimeter; that is to say, the heat evolved in the chamber is measured by a current of cold water. The appliances for measurement of both the respiratory products and the heat given off from the body differ in important respects from those of any other apparatus with which we are familiar.

The most important feature of the respiration calorimeter is a metal-walled chamber in which a man lives, eats, drinks, works, and sleeps. Provision is made for ventilating the chamber and for regulating the temperature and moisture of the air within it. The volume of the ventilating air current is measured and samples for analysis are taken before and after it passes through the chamber, thus obtaining the amounts of carbon dioxide and water in the respiratory products. The food, drink, feces, and urine are weighed and analyzed, and their potential energy is determined, as is the kinetic energy given off from the body in the forms of heat and external muscular work.

The devices for measuring the heat given off from the body include: (1) Arrangements to prevent gain or loss of heat in the chamber either by the passage of heat through the walls or the bringing in and taking out of heat in the ventilating air current; (2) arrangements by which the heat given off in the chamber, by the body or otherwise, is carried out by the current of water above referred to. This current, which is conveyed by copper pipes, comes into the chamber at a low temperature, passes around the interior, absorbs the heat, and goes out correspondingly warmer. The quantity of the water and the rise of temperature show how much heat is carried out. The measurements of temperature of the inner walls of the apparatus, the air inside, and the incoming and outgoing air and water currents are made chiefly by electrical means and are very delicate, differences of one-hundredth of

a degree being easily determined. By regulating the temperature of the water current when it enters the chamber and its rate of flow, the temperature of the interior air and walls can be kept almost exactly constant. When slight changes of interior temperature do occur the corresponding amounts of heat taken up or given off by the interior air and parts of the apparatus are readily determined. Applying the corrections, generally very small, for such changes of interior temperature, the heat gained by the water current in passing through the chamber is the measure of the amount of heat developed in the chamber.

The accuracy of the apparatus and of the methods for the determinations of carbon dioxide, water, and heat was tested by heat generated in the chamber by passing an electric current through a resistance coil and also by burning ethyl alcohol within the chamber. In the electrical tests the measurements of heat generated and found were practically identical. In the alcohol tests the average amounts found by actual experiment were: For carbon, 99.9 per cent; hydrogen, 100.6 per cent; and heat, 99.9 per cent of the theoretical amounts. It thus appears that this apparatus when used for the analysis of alcohol and the determination of its heat of combustion gives results nearly, if not quite, as accurate as are obtained by the ordinary laboratory methods which can be used only with small amounts.

The measurements of heat given off from the body of a man inside the chamber are so delicate that very slight bodily movements, such as rising from a chair or turning over in bed, are immediately noticed by the observer, who is constantly watching the galvanometer and thermometers.

The experiments with men, two of the earlier of which are here reported, were undertaken for the study of several problems. The question especially considered here is this: Is the energy given off from the body in the form of heat, or of heat and external muscular work, equal to the potential energy or heat of combustion of the material actually burned in the body? In other words, when the compounds of the food and the body—proteids, fats, and carbohydrates—are burned is their potential energy transformed into the equivalent kinetic energy and into forms which can be measured by the means here used? Or, to state the question more broadly, does the law of the conservation of energy obtain in the living organism?

The experiments with a man generally continued eight days, during the last four days and five nights of which the subject was in the respiration chamber. The diet during each experiment was uniform throughout the whole eight days. The purpose of the preliminary period of four days was to bring the body into at least approximate nitrogen and carbon equilibrium with the food and to make the determination of the amounts of nutrients absorbed as nearly accurate as practicable. The income and outgo of nitrogen were determined during this period,

which thus amounted to a digestion and metabolism experiment. The metabolism of nitrogen, carbon, hydrogen, and energy was determined during the final period of four days.

Two such experiments are here described. In the first of these, called a "rest experiment," the man had as little muscular exercise as he could well have with comfort. In the second, called a "work experiment," he was engaged in quite active muscular exercise. The external muscular work was expended in driving a dynamo which produced an electric current. The latter was measured, thus showing the amount of external muscular work performed, and was passed through a resistance coil and the energy was transformed into heat, which was measured with that given off from the body.

The difference between the income and outgo of energy as measured in these two cases was $+1.5$ and -2.7 per cent, and averaged -0.6 per cent of the income. The amount of energy as measured was in one case more and in one case less than the theoretical amount of potential energy in the material consumed. The larger discrepancy was in experiment No. 6. Certain sources of error in this appear to have been eliminated, at least in part, in later experiments, of which experiment No. 9 was one. In these later experiments the agreement is very close, the energy measured being about 99 per cent of the theoretical. On the whole, the agreement between theoretical amounts of energy transformed and those found in the experiments is as close as could be reasonably expected, in view of the physiological sources of experimental error and the uncertainties as to the correctness of some of the physical and chemical constants used as factors in the calculations of results.

A gradual approach toward a demonstration of the application of the law of the conservation of energy in the living organism has been made in the experimental inquiry of later years. This is notably the case with Rubner's¹ numerous experiments with two dogs in a specially devised respiration calorimeter. In some of the experiments the dogs fasted; in others they had lean meat or fat bacon, or both, for food. The actual determinations were: The weight of the animal at the beginning and end of the experiment and the weights of food and water given and of feces and urine excreted; the percentages of fat in the bacon fed and of nitrogen in the feces and urine; the weights of carbon dioxide and water in the respiratory products, and the amounts of heat given off from the body. No balance of nitrogen or carbon was determined, but equilibrium of each was assumed. The amounts of food and body materials oxidized were calculated from the nitrogen and carbon excreted. The energy of income was calculated from the estimated amounts of compounds oxidized in the body, and the outgo was taken as the heat given off from the body. Nine experiments made in this way gave values ranging from about -5.2 to $+3.2$ per cent

¹ Die Quelle der thierischen Wärme, Ztschr. Biol., 30 (1894), pp. 73-86.

of the total energy as computed, and the average for the whole forty-five days of the experiments showed a difference of less than one-half of 1 per cent between the estimated potential energy of food materials calculated to have been oxidized and the heat given off from the body as measured by the calorimeter.

In the opinion of the author, these experiments prove that the nutrients of the food and the body materials consumed are the sole sources of heat in the animal body. Although the actually determined data of the experiments are so few and the estimates and assumptions so many, there can hardly be a doubt that the opinion is justifiable. The experiments thus tend to confirm the belief that the law of conservation of energy applies in the living organism. The same may be said of the experiments of Studenski, referred to on page 11, even though the data of his experiments, like those of Rubner, have not all the completeness that is to be desired.

In the experiments described in this bulletin, the energy of outgo includes both the heat given off from the body and, in one case, that of a considerable amount of external muscular work.

In the experiment No. 9 (rest), the outgo apparently exceeds the income by about 35 calories per day. This quantity is really quite small. It would correspond to the potential energy of about 4 grams of body fat, or nearly the same weight of butter, or 9 grams of sugar, or 14 grams of bread.

It may be that a small part of the energy which is transformed in the body is given off in some form which the apparatus and methods here used are incapable of measuring. The income and outgo of energy agree as closely, perhaps, as could be expected in view of the possible sources of error and defects in apparatus and methods.

The sources of error and uncertainty in these experiments can, it seems to us, be divided into two classes: those incident to the experimental work as such, and those due to uncertainty as to the physical, chemical, and physiological constants used as factors in the computations.

The chief sources of experimental uncertainty and error appear to be the following:

(1) Appliances for the direct determination of oxygen of income and outgo are still lacking. These determinations of oxygen are needed for aid in estimating the amounts of carbohydrates, water, and oxygen gained or lost by the body during the experiment. Efforts to supply this deficiency are being made.

(2) No determinations were made of the amounts of sulphur, phosphorus, and chlorine of income and outgo. These more complete chemical determinations are needed to throw light upon the character of the proteids and other nitrogenous compounds burned and stored or lost in the body.

(3) No provision has yet been made for the measurement and analysis

of the volatile organic compounds given off from the body, for example, the gaseous products of bacterial action in the intestines. Research elsewhere, however, has shown them to be extremely small,¹ and it is hardly probable that they would materially affect the results.

(4) The ordinary methods for the sampling and analysis of food and excretory products are not as accurate as is to be desired. Considerable attention has been given to this subject in connection with the present investigation.

(5) Among the physical constants used in computing the results of the experiments the following are of more or less uncertain accuracy. The factor 0.592 is here employed for the latent heat of vaporization of water at 20° C, which is about the usual temperature of the chamber. This factor is derived from the formula of Regnault and is apparently not very far from the truth. The exact value, however, remains to be determined. Furthermore, the conditions of vaporization in the respiration chamber are different from those of the experimental determinations upon which the value 0.592 is based. It is not impossible that accurate determinations of the latent heat of vaporization of water under the conditions that obtain in the chamber of the respiration calorimeter may call for a change in this factor sufficient to measurably affect the results.

(6) The heat of combustion of ethyl alcohol is here taken as 7.067 calories per gram, the average of a considerable number of determinations made in this laboratory. It agrees quite closely with Berthelot's figure 7.079, which is the average of but two determinations. Berthelot's determinations were made with a bomb calorimeter of his own invention, ours with a modified form used in this laboratory. Exact determinations of the heat of combustion of such substances are difficult and the results of individual determinations differ considerably. Efforts are now being made to learn somewhat more of the sources of error, in the hope of obtaining more certain results. It is of course possible that later experiments may call for a different factor. Meanwhile it may be said that agreement of the results obtained by the bomb and respiration calorimeters tend to confirm the accuracy of both.

The measurements of the income and outgo of heat in the respiration calorimeter by the electrical methods above described were practically identical. This implies that the apparatus as a calorimeter gives very accurate results. It also tends to confirm the correctness of the determinations of the heat of combustion of alcohol. The inference would be that the discrepancies between the theoretical amounts of heat and those measured in the experiments with men must be due in

¹ See Billings, Mitchell, and Bergey, On the composition of expired air and its effects upon animal life: Washington, Smithsonian Institution, 1895; and Bergey, Methods for the determination of organic matter in air: Washington, Smithsonian Institution, 1896.

part to other sources of error than those of the actual measurements by the calorimeter.

Considering the respiration calorimeter as an apparatus for the analysis of alcohol and the determination of its heat of combustion on a large scale, the results obtained compare with the theoretical values for carbon and hydrogen and those obtained with the bomb calorimeter for heat of combustion, as in Table 35, which follows. The average figures in this table represent the totals of Table 19, p. 72.

TABLE 35.—*Analysis and determination of heat of combustion of alcohol by the respiration calorimeter.*

Alcohol test experiment.	Carbon.	Hydrogen.	Heat of combustion per gram.
	<i>Per cent.</i>	<i>Per cent.</i>	<i>Calories.</i>
No. 1	52.17	13.08	7.007
No. 2	52.12	13.04	7.126
No. 3	52.85	<i>a</i> [13.84]	7.013
No. 4	<i>a</i> [50.34]	<i>a</i> [14.19]	7.096
No. 5	52.59	13.16	7.069
No. 6	51.44	13.21	7.030
No. 7	52.17	13.20	<i>a</i> [7.219]
No. 8	51.91	13.18	7.049
No. 9	51.86	13.01	7.071
Average	52.12	13.12	7.062
Theoretical; heat of combustion by bomb calorimeter	52.17	13.04	7.067

a Omitted from averages on account of obvious errors.

(7) There are numerous possibilities of slight errors in the physiological constants and assumptions used in the computations of the results obtained with a man in the respiration chamber of the calorimeter. Of these the more important are the following: One of the chief sources of uncertainty in metabolism experiments with man and animals, in which the balance of income and outgo is determined, has to do with the quantity and composition of the materials actually absorbed from the food in the alimentary canal during the experimental period. The best that can be done here is to endeavor to have the diet and other conditions of the experiment as nearly uniform as possible for the time covering not only the experimental period but also several preceding days, and to make the experimental period as long as practicable. In the experiments here described the whole period is made eight days, of which the last four are given to the metabolism experiment proper.

(8) The amounts of protein and fat gained or lost by the body during the period of actual experiment, namely, the four days which the subject spends in the chamber, are computed from the observed gain or loss of nitrogen and carbon. In these computations it is assumed that the body gains or loses no compounds containing nitrogen and carbon

except protein and fats. Any possible difference between the store of carbohydrates at the beginning and that at the end of the experiment is thus left out of account. In making the computations it is assumed that the protein compounds—that is proteids and other nitrogenous compounds—contain collectively 16 per cent of nitrogen and 53 per cent of carbon, and that the fats contain 76.5 per cent of carbon. These figures are arbitrary, and though based upon the best available data may differ considerably from the actual facts. The heats of combustion of the proteids and fats thus estimated to be gained or lost are taken as 5.5 calories and 9.4 calories per gram, respectively.¹ These values, like the chemical constants just cited, are probably more or less incorrect, and it is not impossible that the errors introduced by their use may be sufficient to account for a considerable share of the discrepancy between the estimated income and the measured outgo in the later experiments with man.

(9) Still another possibility of error is found in the so-called nitrogen lag in the urine; that is to say, in the period between the end of the experiment and the final excretion of the nitrogen which belongs to the experimental period. We have assumed that when the diet and muscular work have been performed for a period of eight days, of which the last four were spent in the respiration chamber, the amount of nitrogen in the urine collected from 7 a. m. to 1 a. m. is equivalent to the amount metabolized in the same period. While this assumption would probably be more or less incorrect for any given day, we have believed it would be not far out of the way on the average. We have, however, collected and analyzed the urine for each six hours during the experiment and for similar periods during the twelve or twenty-four hours after the end of the experiment. The results of these determinations have not yet been published.

(10) Finally, a possible source of error is in changes of temperature of the body. If the body is warmer or colder at the end of the experimental period than at the beginning allowance should be made for the gain or loss of heat. The amount of this change of heat is dependent upon the change of temperature, and the specific heat of the body. To measure the temperature of the body exactly is not easy. The specific heat of the body is not precisely known nor could it at best be stated with precision in any given case, because it would depend upon the weight and specific heats of different constituents, as water, proteids, fats, and other compounds. This subject is receiving consideration in connection with the experiments. It will suffice to say here that measurements of body temperature now made with a thermometer by the ordinary clinical methods did not reveal any marked differences between the temperature at the hour when each experimental period began and that when it ended, namely, at 7 a. m. in each case.

¹ U. S. Dept. Agr., Office of Experiment Stations Bul. 21, pp. 126-133.

In brief, so far as the sources of error are those of chemical and physical analyses and manipulation, the attempt is being made to reduce them to a minimum. In so far as they are of physiological origin and practically beyond control the attempt is made to eliminate them so far as practicable by long experimental periods and by duplication of the experiments.

Meanwhile it is safe to say that in view of the physiological uncertainties and sources of error and the probable incorrectness of some of the physical and chemical constants employed, the differences between the estimated income and measured outgo of energy in the experiments with men are not at all surprising.

In view of these defects and sources of error in methods and apparatus we would perhaps be unwarranted in assuming that the experiments thus far made completely demonstrate the application of the law of the conservation of energy in the human organism. They do, however, seem to us to be reasonably near to such demonstration, especially when we take into account the possible sources of error—chemical, physical, and physiological—which have been discussed above.

It is certainly safe to assume that the principle followed in the experiments is correct, and that the apparatus and methods are accurate to the degree required for the experimental study of a large variety of the fundamental problems of biological chemistry and physics. Among these are the metabolism of energy and the production of heat by the body in the performance of its ordinary functions, as circulation, respiration, and digestion; the relations of muscular and mental work to the metabolism of matter and energy; the demands of the body for nutriment under different conditions of work and rest; the duties performed by the different nutrients of food in supplying the needs of the body; and finally, the nutritive values of food materials and the amount and proportions best adapted to the needs of people of different classes, with different occupations, and in different conditions of life. That such inquiries may be valuable for the study of food and nutrition in disease is equally apparent. Of course they are fundamentally necessary for a more thorough understanding of the economy of feeding domestic animals.